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REVIEW ARTICLE

Robotic gastrectomy for gastric cancer: systematic review and future directions

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Abstract

Background Robotic gastrectomy (RG) using the da Vinci Surgical System for gastric cancer was approved for national medical insurance coverage in Japan in April 2018, and its number has been rapidly increasing since then.

Aim We reviewed and compared current evidence on RG and conventional laparoscopic gastrectomy (LG) to identify the differences in surgical outcomes.

Methods Three independent reviewers systematically reviewed the data collected from a comprehensive literature search by an independent organization, focusing on the following nine endpoints: mortality, morbidity, operative time, estimated blood loss volume, length of postoperative hospital stay, long-term oncologic outcome, quality of life, learning curve, and cost.

Results Compared to LG, RG has lower intraoperative blood loss volume, shorter length of hospital stay, and shorter learning curve, but both procedures have similar mortality. Contrarily, its disadvantages include longer procedural time and higher costs. Although the morbidity rate and long-term outcomes are almost comparable, RG showed superior potentials. Currently, the outcomes of RG are considered comparable to or better than LG.

Conclusion RG might be applicable to all gastric cancer patients who fulfill the indication of LG at institutions that meet specific criteria and are approved to claim the National Health Insurance costs for the use of the surgical robot in Japan.

Keywords Gastrectomy · Minimally invasive surgical procedures · Robotics · Stomach neoplasms

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Abbreviations

RG	Robotic gastrectomy
LG	Laparoscopic gastrectomy
GC	Gastric cancer
OG	Open gastrectomy
DVSS	da Vinci surgical system
RCT	Randomized controlled trial
QOL	Quality of life
PSM	Propensity score matching
TG	Total gastrectomy
PG	Proximal gastrectomy
CI	Confidence interval
CD	Clavien–Dindo classification
OS	Overall survival
RFS	Recurrence-free survival
ESSQS	Endoscopic surgical skill qualification system
EQ-5D	EuroQol 5 dimension
HSRS	Hinotori™ surgical robot system

Background

Gastric cancer (GC) is the fifth most common malignant tumor and the fourth leading cause of cancer-related deaths worldwide [1]. Surgical resection is the only curative treatment option, and regional lymphadenectomy is recommended as part of radical gastrectomy [2, 3]. Recently, laparoscopic gastrectomy (LG) has gained widespread use as it is a minimally invasive and safe curative procedure for both early and advanced GC with comparable outcomes to open gastrectomy (OG) [4–9]. However, LG has several limitations, including limited range of motion with straight forceps and tremors in the hand. Therefore, a novel technology that can overcome these limitations is required.

The da Vinci Surgical System (DVSS; Intuitive Surgical, Sunnyvale, the USA) is an advanced robotic technology that plays a pivotal role in robotic surgery. DVSS has the following three components: (i) surgeon console, (ii) patient cart, and (iii) vision cart. It provides the surgeon with a three-dimensional, tenfold magnified view of the operating field, replicates the natural hand–eye coordination axis in the ergonomically designed surgeon's console, offers a high degree of freedom through its articulating surgical instruments, stabilizes the surgeon's tremor and scales motion [10]. Since the first report of robotic gastrectomy (RG) by Hashizume et al. in 2003 [11], newer RG techniques have been developed based on those used for LG. Furthermore, RG was approved for national medical insurance coverage in Japan in April 2018 [12]; since then, the number of RG procedures has significantly increased nationwide. We have previously performed a systematic review about the current status of RG for GC in 2019 [13]. We found that RG was a safe and feasible procedure that may reduce postoperative morbidity, but RG was still not highly recommended for patients with clinical stage I/II GC at institutions that meet specific criteria at that time. Recently, prospective studies including randomized controlled trials (RCTs) [14–23] and large-scaled multi-institutional retrospective studies that focused on RG have increased worldwide [24–29], and we considered that the time was ripe to conduct a new literature review about the clinical efficacy of RG for GC.

Materials and methods

This systematic review was performed according to the Minds manual for clinical practice guideline development 2020 ver.3.0 [30]. A comprehensive search of electronic databases, including MEDLINE, Cochrane Library, and Japan Medical Abstracts Society (Ichushi), was performed by the Japan Medical Library Association using the search terms "Stomach neoplasms," "Robotics," "Surgery," "Cohort studies," "Meta-Analysis," "Randomized controlled trial," "Multicenter study," "Comparative study," and "Practice guideline." Based on the previous systematic review [13], all English articles published between January 1, 1990 and March 31, 2022 were included. The reference lists of the included articles were also reviewed to identify relevant reports missed during the primary search. Articles that should be included were selected by three independent reviewers (S.S., S.H., and K.S.) who were part of the cooperative guideline committees for the Japan Society for Endoscopic Surgery, and they evaluated evidence for the following categories: mortality, morbidity, operative time, estimated blood loss volume, length of postoperative hospital stay, oncologic long-term outcome, quality of life (QOL), learning curve, and cost. When the data were insufficient after the primary search, secondary hand-searches were conducted by each reviewer from January 1, 1990 to December 31, 2022.

Results

Literature search and characteristics of reviewed articles

The primary literature search identified 258 papers; 24 papers were selected after excluding duplicate studies, those in written in languages other than English, animal studies, conference proceedings, and review articles. As nine more publications were included during the secondary search, 33 papers were finally selected for review (Fig. 1). Among them, 15 papers overlap with the previous review. The details of the selected publications are provided in Table 1. The 33 selected studies included four

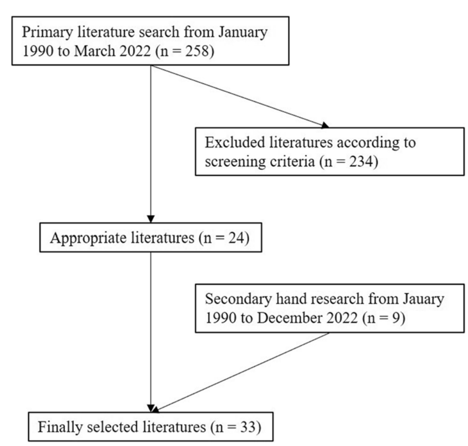

Fig. 1 Flow chart of literatures selection

Table 1 Summary of the selected articles on RG

Study design	Authors	Year	Country	Patients of RG (*n*)	Short-term	Long-term	Learning curve	QOL	Cost
Randomized control trial	Wang G et al. [14]	2016	China	158	✓				–
	Pan HF et al. [15]	2017	China	102	✓	–	–	–	–
	Lu J et al. [16]	2021*	China	150	✓				
	Ojima T et al. [17]	2021*	Japan	119	✓				
Prospective (multi-institution)	Kim HI et al. [18]	2016	South Korea	223	✓				✓
	Uyama I et al. [19]	2019	Japan	328	✓			✓	✓
	Okabe H et al. [20]	2019	Japan	115	✓				
Prospective (single-center)	Park JY et al. [21]	2014	South Korea	30				✓	
	Tokunaga M et al. [22]	2016	Japan	120	✓				
	Hikage M et al. [23]	2020*	Japan	120		✓			
Retrospective (multi-institution)	Parisi A et al. [24]	2017	Italy	222	✓				
	Ryan S et al. [25]	2020*	USA	631	✓				
	Li ZY et al. [26]	2021*	China	1829	✓	✓			✓
	Suda K et al. [27]	2022*	Japan	2675	✓				
	Shimoike N et al. [28]	2022*	Japan	336	✓		✓		
	Suda K et al. [29]	2022*	Japan	326		✓			
Retrospective (single-center)	Wang WJ et al. [31]	2019	China	254	✓				
	Shibasaki S et al. [32]	2020*	Japan	359	✓				
	Hikage M et al. [33]	2021*	Japan	345	✓	✓			
	Li ZY et al. [34]	2021*	China	519	✓				
	Omori T et al. [35]	2022*	Japan	210	✓				
	Tian Y et al. [36]	2022*	China	463	✓	✓			✓
	Gao G et al. [37]	2022*	China	441	✓	✓			
	Obama K et al. [38]	2018	South Korea	315		✓			
	Gao Y et al. [39]	2019	China	163		✓			✓
	Nakauchi M et al. [40]	2021*	Japan	157		✓			
	Park SS et al. [41]	2012	South Korea	60			✓		
	Huang KH et al. [42]	2014	Taiwan	72			✓		
	Zhou J et al. [43]	2015	China	105			✓		
	Shibasaki S et al. [44]	2022*	Japan	100			✓		
	Suda K et al. [45]	2015	Japan	88					✓
Meta-analysis/Systematic review	Guerrini GP et al. [46]	2020*			✓	✓	✓	✓	✓
	Shibasaki S et al. [13]	2020*			✓	✓	✓	✓	✓

RG,robotic gastrectomy, *QOL* quality of life

*Newly added references that were not included in our previous review article

RCTs [14–17], three multi-institutional prospective studies [18–20], three single-center prospective cohort studies [20–22], six large-scale multi-institutional retrospective studies [24–29], and 15 single-center retrospective studies [31–45]. The single-center retrospective studies were selected because they were large-scale, single-center, retrospective studies that included > 200 RG cases using the propensity score matching (PSM) analysis for short-term outcome evaluation [31–37], that included > 100 RG cases with a median follow-up period of ≥ 30 months for long-term outcomes evaluation after RG [26, 29, 33, 36–40], or they have assessed the learning curve of RG [27, 41–44], and cost [18, 19, 26, 36, 39, 45]. In addition to the previous systematic review [13], one meta-analysis assessing the differences in outcomes between RG and LG was included [46]. To evaluate the patient characteristics, the proportions of patients diagnosed with stage ≥ II GC and who underwent total gastrectomy (TG) or proximal gastrectomy (PG) were investigated for each of the 24 included studies. Additionally, the follow-up periods were also investigated for each of the nine included studies to evaluate the long-term oncological outcomes.

Mortality

As shown in Table 2, the four RCTs and four prospective studies reported no mortality after RG [14–20, 22]. In several large-scale multi-institutional retrospective analyses from East Asia, the mortality rate of RG was very low ranging from 0% to 0.2%, with no significant differences between RG and LG [26–28]. Similarly, eight large-scale single-center retrospective analyses have reported low mortality rates that ranged from 0% to 0.9%, showing no significant difference between RG and LG [31, 32, 34–37] (Table 3). Although a large-scale multi-institutional retrospective analysis from the US indicated a slightly higher mortality rate of RG (4.5%), that of LG (2.7%) was also slightly higher, indicating no significant difference [25]. A recent meta-analyses by Guerrini et al. reported a mortality rate for RG of 0.36% (16/4378), which was comparable to that of LG (0.30, 31/10354), with odds ratio (OR) of 1.43 [95% confidence interval (CI) 0.77–2.65, $p=0.25$] [46] (Table 3).

Morbidity

To reproducibly evaluate morbidity, Clavien–Dindo classification (CD) grade ≥ IIIa complications were included during analysis, as these complications can be life-threatening and require surgical, endoscopic, or radiological interventions which could result in significantly extended hospital stay and increased medical cost [47, 48]. As shown in Table 2, three out of four RCTs showed no significant differences in morbidity between RG and LG [14–16]. Contrarily, the RCT reported by Ojima et al. showed that the rate of total complications for RG was significantly lower than that of LG (5.3% vs. 16.2%, $p=0.01$) [17], although the primary endpoint of intra-abdominal infectious complications, including anastomotic leakage, pancreatic fistula, and intra-abdominal abscess, was not met. When CD grade II complications were included, the recent two RCTs reported by Lu et al. (7.7% vs. 16.9%, $p=0.006$) and Ojima et al. (8.8% vs. 19.7%, $p=0.02$) demonstrated the superior outcomes of RG to LG [16, 17]. The non-randomized prospective study by Kim et al. reported a morbidity rate for RG of as low as 1.1%, which was comparable to that of LG (1.1%, $p=0.999$) [18]. Our prospective multi-institutional study has shown that RG significantly reduced the morbidity rate from 6.4% after LG to 2.45% after RG ($p=0.0018$), which was the primary endpoint of this non-randomized prospective trial [19]. The two single-arm prospective studies by Okabe et al. and Tokunaga et al. reported a CD grade ≥ IIIa morbidity rate of 2.6% and 3.3% after RG, respectively [20, 22]. The four large-scaled multi-institutional retrospective studies showed a low morbidity rate ranging from 1.3% to 5.4% [24, 26–28] (Table 3). These findings were almost comparable to those of LG, ranging from 2.9% to 4.7%. Among them, two retrospective cohort studies using real-world big data demonstrated comparable morbidity rates between RG and LG (Li et al. RG 2.5% vs. LG 2.9%; Suda et al. RG 4.9% vs. LG 3.9%) [26, 27]. Among the single-center, large-scaled, and retrospective comparative studies that used PSM analyses, three studies demonstrated that RG significantly reduced morbidity, as compared to LG (Wang et al. 8.9% vs. 17.5%, $p=0.002$; Shibasaki et al. 3.7% vs. 7.6%, $p=0.033$; Omori et al. 1.0% vs. 4.8%, $p=0.007$) [31, 32, 35]. Additionally, Hikage et al. showed that RG had a significantly lower rate of CD grade ≥ II intra-abdominal infectious complications than LG (4.4% vs. 9.4%, $p=0.015$), but not in total complications (RG vs. LG 13.2% vs. 18.4%, $p=0.074$) [33]. A meta-analyses by Guerrini et al. showed that the rate of CD grade ≤ IIIa surgical complications was significantly lower in RG than in LG [4.13% (150/3631) vs. 6.44 (498/7727), OR 0.66, 95% CI 0.49–0.88, $p=0.005$] [46] (Table 3).

Duration of procedure

As shown in Table 2, three RCTs have indicated that the RG duration was significantly longer than that for LG (Wang et al. 242.7 vs. 192.4 min, $p=0.002$; Lu et al. 201.2 vs. 181.6 min, $p<0.001$; Ojima et al. 297 vs. 245 min, $p=0.001$) [14, 16, 17], whereas only one RCT reported by Pan et al. showed comparable operative time between RG and LG [15]. The non-randomized prospective study by Kim et al. also indicated that the RG duration was significantly longer than the LG duration (RG: 221 vs. LG: 178 min, $p<0.001$) [18]. Three prospective studies reported an RG duration that ranged from 313 to 372 min [19, 20, 22]. Most multi-institutional and single-center retrospective studies have shown that the RG duration was significantly longer than the LG duration [24, 26, 27, 32–34, 36, 37], as shown in Table 3. Most of these studies have shown that the differences in operative time between RG and LG ranged from approximately 20–50 min. Liu et al. have reported the reasons for the longer RG duration; they demonstrated that while the effective time and number of exchanging instruments did not differ between RG and LG, junk time, i.e., instrument setup and docking or positioning of surgical arms, and the time required for exchanging instruments was significantly longer for RG than for LG [49]. A previous meta-analysis showed that the mean operative times of RG and LG were 267.34 and 220.48 min, respectively. The operative time was also significantly shorter in LG than in RG ($p<0.001$) [46]. In contrast, Wang et al. have indicated that there were no significant differences in the total operative time between RG and LG [31]. Furthermore, Omori et al. recently reported that the operative time of RG was significantly shorter than that of LG [35], suggesting that the duration of RG could be shortened through training and expertise.

Table 2 Short-term outcomes in randomized control trials (RCTs) or prospective studies

Reference (year/country)	Study design	Enrolled patients (*n*)	Patients for analysis (*n*)	≥ Stage II (%)	TG or PG (%)	Mortality (%)	Morbidity[1] (%)	Operative time (min)	Estimated blood loss (mL)	Postop. hospitalization (days)
Wang G et al. [14] (2016/China)	RCT (single-center)	RG: 158 OG: 153	RG: 151 OG: 145	76 79	37 31	0 0 (N.D.)	2.6 2.8 ($p=0.756$)	243 192 ($p=0.002$)	94 153 ($p<0.001$)	5.6 6.7 ($p=0.021$)
Pan HF et al. [15] (2017/China)	RCT (single-center)	RG: 102 LG: 61	RG: 102 LG: 61	78 89	65 74	0 0 (N.D.)	1.0 6.6 (N.D.)	153 152 ($p=0.717$)	41 84 ($p<0.001$)	3.8 5.4 ($p<0.001$)
Lu J et al. [16] (2021/China)	RCT (single-center)	RG: 150 LG: 150	RG: 141 LG: 142	N.D	0 0	0 0 (N.D.)	1.4 1.4 (N.D.)	201 182 ($p<0.001$)	41 56 ($p=0.045$)	7.9 8.2 ($p=0.062$)
Ojima T et al. [17] (2021/Japan)	RCT (two-center)	RG: 119 LG: 122	RG: 113 LG: 117	42 40	41 32	0 0 ($p=1.000$)	5.3 16.2 ($p=0.01$)	297 245 ($p=0.001$)	25 25 ($p=0.18$)	12 13 ($p=0.93$)
Kim HI et al. [18] (2016/South Korea)	Prospective (multi-institution)	RG: 223 LG: 211	RG: 185 LG: 185	19 10	16 16	0 0 (N.D.)	1.1 1.1 ($p=0.999$)	221 178 ($p<0.001$)	50 55 ($p=0.318$)	6 6 ($p=0.862$)
Uyama I et al. [19] (2019/Japan)	Prospective, (multi-institution)	RG: 328	RG: 326	12	22	0	2.45	313	20	9
Okabe H et al. [20] (2019/Japan)	Prospective (multi-institution)	RG: 115	RG: 115	30	37	0	2.6	372	15	12
Tokunaga M et al. [22] (2016/Japan)	Prospective (single-center)	RG: 120	RG: 120	1	12	0	3.3	348.5	19	9

TG total gastrectomy, *PG* proximal gastrectomy, *RCT* randomized controlled trial, *RG* robotic gastrectomy, *LG* laparoscopic gastrectomy, *OG* open gastrectomy, *N.D.* not described

[1]Morbidity included the Clavien–Dindo classification grade IIIa ≤ complications

Table 3 Short-term outcomes in retrospective studies

Reference (year/country)	Study design	Enrolled patients (n)	Patients for analysis (n)	≥ Stage II (%)	TG or PG (%)	Mortality (%)	Morbidity[1] (%)	Operative time (min)	Estimated blood loss (mL)	Postop. hospitalization (days)
Parisi A et al. [24] (2017/Italy)	Retrospective (multi-institution)	RG: 222 LG: 227 OG: 577	RG: 151 LG: 151 OG: 302 (PSM)	44 44 53	26 32 32	(N.D.)	1.3 4.7 6.0 (N.D.)	365 220 199 ($p<0.001$)*	118 96 127 ($p=0.002$)*	8.9 9.1 12.7 ($p<0.001$)*
Ryan S et al. [25] (2020/USA)	Retrospective (multi-institution)	RG: 631 LG: 1262 (PSM)	RG: 631 LG: 1262 (PSM)	66 66	28 28	4.5 2.7 ($p=0.101$)	N.D	N.D	N.D	10.2 11.6 ($p<0.001$)
Li ZY et al. [26] (2021/China)	Retrospective (multi-institution)	RG: 1829 LG: 3573	RG: 1776 LG: 1776 (PSM)	35 35	31 31	0.2 0.1 ($p=1.000$)	2.5 2.9 (N.D.)	248.5 220 ($p<0.001$)	127 143 ($p<0.001$)	9.2 9.3 ($p=0.371$)
Suda K et al. [27] (2022/Japan)	Retrospective (multi-institution)	RG: 2675 LG: 7206	RG: 2671 LG: 2671 (PSM)	N.D	14 14	0.2 0.1 ($p=0.754$)	4.9 3.9 ($p=0.084$)	354 268 ($p<0.001$)	20 15 ($p=0.149$)	10 11 ($p<0.001$)
Shimoike N et al. [28] (2022/Japan)	Retrospective (multi-institution)	RG: 336	RG: 336	33	24	0	5.4	370	0	10
Wang WJ et al. [31] (2019/China)	Retrospective (single-center/PSM)	RG: 254 LG: 281	RG: 223 LG: 223 (PSM)	76 76	43 44	0.9 0.4 ($p=0.559$)	8.9 17.5 ($p=0.002$)	242 238 ($p=0.246$)	149 144 ($p=0.311$)	10.2 11.6 ($p<0.001$)
Shibasaki S et al. [32] (2020/Japan)	Retrospective (single-center/PSM)	RG: 359 LG: 1042	RG: 354 LG: 354 (PSM)	38 37	30 29	0.6 0.3 ($p>0.999$)	3.7 7.6 ($p=0.033$)	360 347 ($p=0.001$)	37 28 ($p=0.005$)	12 13 ($p=0.001$)
Hikage M et al. [33] (2021/Japan)	Retrospective (Single-center/PSM)	RG: 345 LG: 835	RG: 342 LG: 342 (PSM)	7 5	16 15	N.D	13.2[#] 18.4[#] ($p=0.074$)	321 282 ($p<0.001$)	15 14 ($p=0.412$)	8 9 ($p=0.041$)
Li ZY et al. [34] (2021/China)	Retrospective (single-center/PSM)	RG: 519 LG: 957	RG: 516 LG: 516 (PSM)	59 60	0 0	0 0.2 ($p=1.000$)	2.7 3.7 ($p=0.376$)	228 201 ($p<0.001$)	112 139 ($p<0.001$)	7.2 7.5 ($p=0.104$)
Omori T et al. [35] (2022/Japan)	Retrospective (single-center/PSM)	RG: 210 LG: 979	RG: 210 LG: 210 (PSM)	48 48	32 35	0 0.5	1.0 4.8 ($p=0.007$)	208 231 ($p=0.005$)	13 42 ($p<0.001$)	7 8 ($p<0.001$)
Tian Y et al. [36] (2022/China)	Retrospective (single-center/PSM)	RG: 463 LG: 877	RG: 456 LG: 456 (PSM)	65 68	20 21	0.2 1.0 ($p=0.339$)	2.7 3.2 ($p=0.916$)	205 185 ($p<0.001$)	74 78 ($p<0.001$)	7.3 7.6 ($p=0.218$)

Table 3 (continued)

Reference (year/country)	Study design	Enrolled patients (*n*)	Patients for analysis (*n*)	≥ Stage II (%)	TG or PG (%)	Mortality (%)	Morbidity[1] (%)	Operative time (min)	Estimated blood loss (mL)	Postop. hospitalization (days)
Gao G et al. [37] (2022/China)	Retrospective (single-center/PSM)	RG: 441 LG: 723	RG: 410 LG: 410 (PSM)	88 87	0 0	0.5 0.5 ($p = 1.000$)	4.9 6.3 ($p = 0.363$)	205 185 ($p < 0.001$)	139 167 ($p < 0.001$)	9.0 9.1 ($p = 0.371$)
Guerrini GP et al. [46]	Meta-analyses	RG LG	5402 12,310			0.36 (16/4378) 0.30 (31/10354) ($p = 0.25$)	4.13 (150/3631) 6.44 (498/7727) ($p = 0.005$)	267.34 220.48 ($p < 0.001$)	98.77 115.02 ($p < 0.001$)	8.67 9.29 ($p = 0.11$)

TG total gastrectomy, *PG* proximal gastrectomy, *RG* robotic gastrectomy, *LG* laparoscopic gastrectomy, *OG* open gastrectomy, *PSM* propensity score matching, *N.D.* not described

*The *p* value for the three groups was shown, and the statistical comparison between each group was not provided

#Morbidity included the Clavien–Dindo classification grade II or higher complications

[1]Morbidity included the Clavien–Dindo classification grade IIIa ≤ complications

Blood loss

As shown in Table 2, three RCTs have reported significantly lower intraoperative estimated blood loss during RG than during either LG or OG (Wang et al. 94.2 vs. 152.8 ml; Pan et al. 41.3 vs. 83.7 ml; Lu et al. 41.2 vs. 55.7 ml) [14–16], whereas the RCT conducted by Ojima et al. showed no significant difference between RG and LG (RG 25 vs. LG 25 ml, $p = 0.18$) [17]. The non-randomized prospective study by Kim et al. has also shown no significant difference in the estimated blood loss between RG and LG (RG 50 vs. LG 55 ml, $p = 0.318$) [18]. Other prospective studies from Japan have shown that RG had a low intraoperative blood loss, ranging from 15 to 20 ml [19, 20, 22]. The results were different among two multi-institutional retrospective studies using big real-world data; Li et al. demonstrated that RG had significantly lower intraoperative blood loss than LG (126.8 vs. 142.5 ml, $p < 0.0001$) [26], whereas we have shown no significant differences between RG and LG (20 vs. 15 ml, $p = 0.149$) [27], as shown in Table 3. Among seven single-center retrospective studies, four showed the superiority of RG in decreasing the amount of intraoperative blood loss [34–37], whereas the other two studies showed comparable values between RG and LG [31, 33]. Most of these studies have shown the difference in estimated intraoperative blood loss between RG and LG, which was approximately 20 ml. Although our previous study indicated that RG increased the intraoperative blood loss than LG (RG 37 vs. LG 28, $p = 0.005$) [32], the amounts in both groups were too small to determine a practical significance. A meta-analysis revealed significantly lower estimated blood loss in RG than in LG (98.77 vs. 115.02 ml, $p < 0.001$) [46].

Length of postoperative hospital stay

As shown in Table 2, two RCTs reported shorter postoperative hospital stay after RG than after LG or OG (Wang et al. 3.75 vs. 5.36 days; $p < 0.001$; Pan et al. 5.6 vs. 6.7 days; $p = 0.002$) [14, 15], whereas two RCTs and one non-randomized prospective study have reported comparable duration between RG and LG (Lu et al. 7.9 vs. 8.2 days; Ojima et al. 12 vs. 13 days; Kim et al. 6 vs. 6 days) [16–18]. The study conducted in Japan [17] showed a relatively longer duration in both groups which could be attributed to its universal coverage of the health insurance system [50]. In fact, prospective studies from Japan reported that the duration after RG ranged from 9 to 12 days [19, 20, 22]. Most multi-institutional and single-center retrospective studies reported shorter postoperative hospital stay after RG than after LG with a difference of 1 day [24, 25, 27, 31–33, 35], or comparable outcomes [26, 34, 36, 37], as shown in Table 3. The meta-analysis showed that the duration was insignificantly shorter in the RG group than in the LG group (RG 8.67 vs. LG 9.29 days, $p = 0.11$) [46].

Oncologic long-term outcomes

The number of studies on the long-term outcomes has increased along with the increase in the reports on the short-term outcomes. Altogether, nine studies and one meta-analysis were selected for the evaluation of the oncological long-term outcomes [23, 26, 29, 33, 36–40, 46], as shown in Table 4. Only one prospective study evaluated the oncologic long-term outcomes after RG [23]. Hikage et al. demonstrated a favorable prognosis of RG, with a 5-year overall survival (OS) and 5-year recurrence-free survival (RFS) rates of 96.7% each, despite the fact that 12.5% of patients were diagnosed with advanced GC [23]. Two multi-institutional retrospective studies were analyzed [26, 29]. Li et al. demonstrated that the 3-year OS and disease-free survival and 5-year OS and disease-free survival rates were comparable between RG and LG [26]. Contrarily, we demonstrated that the 3-year OS of RG was significantly superior to that of LG (96.3% vs. 89.6%, $p = 0.009$), as observed using the inverse probability of treatment weighting method, whereas a trend toward an increase in 3-year RFS of RG was observed, as compared to LG (92.3% vs. 87.2%, $p = 0.073$) [29]. Additionally, sub-analyses revealed that RG improved both the 3-year OS (99.7% vs. 94.4%, $p = 0.004$) and 3-year RFS (99.7% vs. 93.7%, $p = 0.003$) rates in patients with pStage IA disease [29]. Furthermore, after propensity matching, RG significantly improved both the 3-year OS (RG 97.1% vs. LG 89.2%; $p < 0.001$) and 3-year RFS (RG 94.2% vs. LG 86.7%, $p = 0.002$) rates [29]. Six single-center retrospective studies compared the long-term oncological outcomes between RG and LG. In all these six studies, there were no significant differences in the long-term outcomes, including 3-year/5-year OS and RFS rates, between RG and LG [33, 36–40]. However, we demonstrated that both 5-year OS and RFS rates of RG were significantly improved, as compared with LG (OS 70.4% vs. 50.2%, $p = 0.039$; RFS 74.1% vs. 44.5%, $p = 0.005$, respectively) among pStage II/III GC patients after PSM [40]. The meta-analysis showed that the recurrence rate was insignificantly lower in the RG group than in the LG group (RG 9.9% vs. LG 13.5%, $p = 0.25$) [46].

Learning curve

To evaluate the learning curve of RG, retrospective studies [28, 41–44] and a review [13] were included. Zhou et al. have evaluated the learning curve for two surgeons skilled in LG using the cumulative summation score. They found that the number of cases required for reaching a learning plateau for the two surgeons was 12 and 14, respectively [43]. Park et al. have reported that the learning curve for three experienced laparoscopic surgeons, as assessed using a nonlinear least-squares method, showed that a stable operating time was achieved after 9.6, 18.1, and 6 cases, respectively [41]. Huang et al. demonstrated that both operative and docking times for RG decreased and stabilized after 25 procedures in experienced surgeons, whereas the operative time for LG stabilized only after 41 cases [42]. A multi-insititutional retrospective study by Shimoike et al. evaluated the learning process of well-experienced surgeons who started robotic surgery after acquisition of the Endoscopic Surgical Skill Qualification System (ESSQS)-qualification, which certifies them as having sufficient skills and experience in LG [44]. In this study, more than half of the 20 operating surgeons had ≥ 100 LG experience, whereas only 5 performed RG on their own for the first time after previously acting as an assistant surgeon for RG. This study suggested that ≥ 11 cases were needed for the participants to reach a learning plateau in terms of operative time and surgeon fatigue [28]. On the other hand, we have reported the learning curves of five surgeons belonging to a younger generation who started RG after 50 or more experiences of RG procedures as an assistant surgeon. Although they had also acquired the ESSQS qualification prior to their first experience with robotic surgery, their learning plateaus were achieved after 5, 7, 7, 8, and 11 cases (median, 7 cases) [44]. Given that several studies have documented that at least 40–60 surgical procedures were required to overcome the learning curve for LG [51, 52], RG has been found to be associated with a shorter learning curve, especially for those who had abundant experience in an assistant surgeon for RG and were familiar with RG ever since the beginning of their career. Shimoike et al. have also indicated that the number of prior LG experiences was not associated with the operative time and incidence of morbidity [28].

QOL

To evaluate the data on postoperative QOL after RG, only two prospective studies and review articles were included [13]. Park et al. have administered the QLQ-C30 and QLQ-STO22 before the procedure, at 1 week post-procedure, and at 1, 3, 6, and 12 months postoperatively [21]. Compared to the preoperative scores, most parameters on both the QLQ-C30 and QLQ-STO22 initially deteriorated at 1 week after surgery but recovered to baseline levels within 3 months. The factors with values that returned to baseline level after 3 months include fatigue, dysphagia, pain, and eating restriction, and these reverted to baseline levels at 1 year postoperatively. Only patients with diarrhea did not recover at 1 year postoperatively [21]. Our multi-institutional prospective trial in Japan evaluated the health outcomes measured using the EuroQol 5 Dimension (EQ-5D) [19]. The EQ-5D score was

Table 4 Summary of the oncologic outcomes of RG

Reference (year)	Study design	Enrolled patients (*n*)	Patients for analysis (*n*)	≥ Stage II (%)	TG/PG (%)	Follow-up period (months)	3-year OS (%)	3-year RFS (%)	5-year OS (%)	5-year RFS
Hikage M et al. [23] (2020/Japan)	Prospective (single-center)	RG: 120	RG: 120	13	13	60	N.D	N.D	96.7%	96.7%
Li ZY et al. [26] (2021/China)	Retrospective (multi-institution)	RG: 1829 LG: 3573	RG: 1776 LG: 1776 (PSM)	65 65	28 28	32.4 31.3	83.5 82.2 (p = 0.240)	82.6 81.3 (p = 0.227)	80.8 79.5 (p = 0.213)	79.8 78.5 (p = 0.205)
Suda K et al. [29] (2022/Japan)	Retrospective (multi-institution)	RG: 326 LG: 757	RG: 311 LG: 311 (PSM)	24 22	22 21	36	97.1 89.2 (p < 0.001)	94.2 86.7 (p = 0.002)	N.D	N.D
Obama K et al. [38] (2018/South Korea)	Retrospective (single center)	RG: 315 LG: 525	RG: 311 LG: 311 (PSM)	19 14	26 25	85	N.D	N.D	93.2 90.7 (p = 0.527)	90.7 92.6 (p = 0.229)
Gao Y et al. [39] (2019/China)	Retrospective (single center)	RG: 163 LG: 339	RG: 163 LG: 163 (PSM)	0 0 (N.D.)	61 56	50.5	76.1 79.8 (p = 0.552)	73.0 68.7 (p = 0.386)	N.D	N.D
Hikage M et al. [33] (2021/Japan)	Retrospective, (Single center)	RG: 345 LG: 835	RG: 342 LG: 342 (PSM)	16 14	16 15	36 48	N.D	N.D	96.4 94.8 (p = 0.532)	95.2 93.4 (p = 0.469)
Nakauchi M et al. [40] (2021/Japan)	Retrospective, (single center)	RG: 157 LG: 657	RG: 61 LG: 61 (PSM)	100 100	31 31	59.5	N.D	N.D	70.4 50.2 (p = 0.039)	74.1 44.5 (p = 0.005)
Tian Y et al. [36] (2022/China)	Retrospective (single center)	RG: 463 LG: 877	RG: 456 LG: 456 (PSM)	65 68	22 24	34	81.2 80.3 (p = 0.648)	76.6 77.0 (p = 0.951)	N.D	N.D
Gao G et al. [37] (2022/China)	Retrospective (Single center)	RG: 441 LG: 723	RG: 410 LG: 410 (PSM)	88 87	0 0	39	75.5 73.1 (p = 0.471)	72.9 71.4 (p = 0.763)	N.D	N.D
Guerrini GP et al. [46] (2020)	Meta-analysis		RG: 1322 LG: 1942				Recurrence rate: 9.9% Recurrence rate: 13.5% (p = 0.25)			

TG total gastrectomy, *PG* proximal gastrectomy, *OS* overall survival, *RFS* recurrence free survival, *RG* robotic gastrectomy, *LG* laparoscopic gastrectomy, *PSM* propensity score matching, *N.D.* not described

[1]UICC classification, 7th edition

[2]JCGC classification, 14th edition

[3]UICC classification, 6th edition

1.0 (0.5920–1.0) preoperatively, 0.8040 (0.3940–1.0) on postoperative day 7, and 1.0 (0.3940–1.0) on postoperative day 30 [19]. However, no comparative study has yet examined postoperative QOL, and the impact of RG at this point cannot yet be determined.

Cost

To evaluate the total cost of RG, six studies plus one meta-analysis were included [18, 19, 26, 36, 39, 45, 46], as shown in Table 5. Kim et al. reported that the per-patient cost was higher for RG than for LG (RG 13,470 vs. LG 8980 US dollars, $p < 0.001$) [18]. Our multi-institutional single-arm prospective trial reported that the surgical cost and per-patient cost of RG were 1,063,800 (950,000–1,158,970) and 1,799,628 JPY [19], respectively, with the total medical cost being higher in patients with morbidity than in those without [morbidity (+): 2,936,159 (2,522,180–5,173,706) vs. morbidity (−): 1,795,506 (1,530,170–3,268,218) JPY, $p = 0.004$] [19]. The multi-institutional retrospective study in China by Li et al. showed that the per-patient cost was higher for RG than for LG (14,185 vs. 10,637 US dollars, $p < 0.001$) [26]. Other single-center retrospective studies have also reported that the per-person operation cost was higher for RG than for LG [36, 39, 45]. A meta-analysis by Guerrini et al. showed that the cost was significantly higher for RG than for LG (12,224.5 vs. 8292.8 US dollars, $p < 0.001$) [46].

Discussion

Compared to our previous review [13], the number of prospective and large-scaled multi-institutional retrospective studies has been increasing. Moreover, the number of large-scaled single-center retrospective studies using PSM analysis has been increasing. In fact, almost half (18/33) of papers included in our review have been published since 2020. This suggests that RG has been widely used worldwide in a short period. Most recent papers have been reported mainly from Japan and China. Therefore, it seems that RG plays an important role in curative resection for GC especially in these two countries. Overall, compared to LG, RG has the advantages of lower intraoperative blood loss volume (approximately 10–40 ml), shorter length of hospital stay (approximately 1 day), shorter learning curve (approximately 6–20 cases), and similar mortality. Contrarily, its disadvantages include longer procedural time (approximately 20–50 min) and higher costs (approximately 1000–5000 US dollars). These outcomes seem to be highly reproducible. Meanwhile, the advantages of RG in terms of the morbidity rate and long-term outcomes seem controversial. Several

Table 5 Summary of the cost for RG vs. LG

Reference (year)	Study design	Enrolled patients (n)	Patients for analysis (n)	Cost per patient
Kim HI et al. [18] (2016/South Korea)	Prospective (multi-institution)	RG: 223 LG: 211	RG: 185 LG: 185 (PSM)	Total cost: 13,470 USD Total cost: 8980 USD ($p < 0.001$)
Uyama I et al. [19] (2019/Japan)	Prospective (multi-institution)	RG: 328 (Single arm)	RG: 326 (Single arm)	Surgical cost: 1,063,800 (950,000–1,158,970) JPY Total cost: 1,799,628 (1,530,170–5,173,706) JPY
Li Y et al. [26] (2021/China)	Retrospective (multi-institution)	RG: 1829 LG: 3573	RG: 1776 LG: 1776 (PSM)	Total cost: 14,185 USD Total cost: 10,637 USD ($p < 0.001$)
Suda K et al. [45] (2015/Japan)	Retrospective (Single-center)	RG: 88 LG: 438	RG: 88 LG: 438	Surgical cost: 7655 USD Surgical cost: 6870 USD (N.D.)
Gao Y et al. [39] (2019/China)	Retrospective (single-center)	RG: 163 LG: 339	RG: 163 LG: 163 (PSM)	Total cost: 1,333,800 (416,200) RMB Total cost: 953,400 (293,900) RMB ($p < 0.001$)
Tian Y et al. [36] (2022/China)	Retrospective (single-center)	RG: 463 LG: 877	RG: 456 LG: 456 (PSM)	Total cost: 13,607 USD Total cost: 10,928 USD ($p < 0.001$)
Guerrini GP et al. [46] (2020)	Meta-analysis	RG LG	682 1373	12,224.5 USD 8292.8 USD ($p < 0.001$)

RG robotic gastrectomy, *LG* laparoscopic gastrectomy, *PSM* propensity score matching, *USD* US dollar, *RMB* Renminbi, *N.D* not described

RCTs and single-center retrospective studies as well as one meta-analysis demonstrated the superior efficacy of RG, as compared to LG, in reducing the morbidity rate [16, 17, 31–33, 35], whereas some RCTs and real-world big data have shown comparable outcomes [14, 15, 18, 26, 27]. Similarly, although most studies have demonstrated that the long-term outcomes were comparable between RG and LG, our multi-institutional study and our single-center retrospective study demonstrated the superiority of RG to LG [29, 40]. Although these findings are similar to our previous review [13], the gathered evidence levels have clearly become more robust. Therefore, we consider that the technical feasibility and oncological safety of RG are at least comparable, or rather have a potential to exceed those of LG. However, some issues need to be discussed further.

First, the impact of the differences in proficiency levels between RG and LG remains unclear. LG was first introduced by Kitano et al. 30 years ago [53]. During these periods, LG was greatly developed by numerous surgeons; thus, it has become a common procedure. Especially in Japan, half of distal gastrectomy cases and a quarter of TG cases were performed by laparoscopic surgery according to the National Clinical Database in 2020 [54]. So far, LG has been recognized as one of the standard treatment options of curative gastrectomy for clinical stage I GC, based on the results of the multi-institutional prospective clinical trials [4, 55], as shown in the Japanese Gastric Cancer Treatment Guidelines 2021 [3], and the indication for LG is likely to expand and include more advanced GC following the positive results of the Japanese randomized trial [9]. These findings suggest that LG has come to the ripening stage. Technical principles and appropriate surgical concepts are shared among many surgeons and many institutions. In fact, many studies have reported very low morbidity rates for LG at $\leq 5\%$ [14, 16, 18, 26, 27, 34–36]. Contrary to LG, RG has a relatively short history. Especially in Japan, the national medical insurance coverage of RG was approved at last in 2018, based on the results of our clinical trial [19]; since then, the number of RG has been rapidly increasing and RG has been weakly recommended as a standard treatment option under certain conditions in the present guidelines [3]. However, the number of RG conducted annually for GC remains to be far less than that of LG for GC [27]. Accordingly, RG seems to be still at the developing stage; thus, there is plenty of room for further improvement. Despite this situation, no reports have indicated that RG worsened the surgical outcomes as compared with LG, as shown in this review. We have successfully proven the safe implementation of RG with a comparable morbidity rate of LG in a Japanese large database study [27]. Collectively, the safety of RG is firmly confirmed. Moreover, most studies conducted in the leading institutions indicated the superiority of RG over LG in terms of morbidity [31–33, 35], suggesting that the discreet implementation of RG could result in the improved safety of gastrectomy in the real clinical setting. We believe that the skills required to fully operate a robot considering the appropriate surgical concept could play a key role in enhancing the clinical benefits of RG [29].

Second, the impact of RG on long-term outcomes needs to be investigated further. The benefits of RG in improving survival were identified only in our studies [29, 40], although most previous reports failed to demonstrate the prognostic benefit of RG over LG. This may be at least partly due to the possibility that RG reduces the risk of some postoperative complications. Various reports have shown that severe postoperative morbidities are associated with impaired long-term prognosis [56]. Additionally, the magnified and clear surgical view and improved range of motion brought about by the DVSS might enable gentler tumor resection along the optimal dissectable layers to be traced. These better operabilities could contribute to reducing the risk for intraoperative dissemination of circulating tumor cells and decreasing systemic inflammatory responses, leading to better recovery and prognosis with a lesser tumor recurrence risk [29]. However, these studies have several major limitations. Further research is required to examine the mechanisms through which RG improves survival and to determine if RG is truly less invasive than LG.

Third, the impact of the LG experience of each operating surgeon on the outcomes of RG needs to be determined. In the present situation, RG is usually launched and subsequently performed by operating surgeons with extensive LG experience [41–44], which might help surgeons to comprehend the principal anatomical knowledge and surgical concept required to complete a gastrectomy safely and precisely with high reproducibly. Contrarily, Shimoike et al. showed that the number of prior LG experiences (≤ 50 vs. > 50 cases) was not associated with operative time and morbidity rate [28]. Similarly, we have successfully proven the safety of RG performed by non-ESSQS–qualified surgeons, who are relatively regarded as inexperienced LG surgeons after satisfactory training to completely utilize the unique characteristics of the DVSS [57]. These findings suggest that prior LG experience may not be mandatory for a surgeon who wishes to learn RG, provided an adequate training system could be established and generalized. Hopefully, this encourages future young surgeons who are interested to learn RG.

The future of RG would depend on the following three important aspects. First, it is necessary to clarify further the efficacy of RG, especially whether RG could lower the degree of difficulty for technically demanding procedures (e.g., TG [58], PG [59], transhiatal procedure for esophagogastric junction cancer [60], radical resection after neoadjuvant chemotherapy [61], and so on). In the retrospective study using the PSM analysis limited to TG, we demonstrated that RTG significantly reduced the incidence of total (3% vs. 13%, $p = 0.019$) and intra-abdominal infectious (1% vs. 9%, $p = 0.023$) complications, as compared to LTG [58]. The OR of complication risk in non-robotic TG was approximately 2–4 times greater, as compared to that in non-robotic minimally invasive gastrectomy in our previous study in which approximately 60%–70% of the entire cohort was distal gastrectomy cases [32, 58]. These findings suggest that TG becomes a good indication for robotic surgery. Further studies are needed to prove that robotic system has greater clinical advantage in technically demanding procedures. Second, we should consider how cost-effectiveness of RG could be improved. To solve this issue, definite evidence that RG improves the long-term outcomes, including the patient's QOL, needs to be established [29, 62]. Now, the current review found that only two retrospective studies from Japan clearly demonstrated the clinical benefits of RG in the long-term. A multicenter RCT is warranted to confirm the reproducibility of these studies. However, at least ≥ 3 years is required to prove this. Therefore, exploring a novel surrogate marker, instead of the OS and RFS, or something worthwhile corresponding to its higher costs is important. Technological advancements in precision medicine (e.g., comprehensive genomic analysis [63] and liquid biopsy [64]) may be of great help in such aspects. Third, further research and development of the novel robotic innovations are essential. As an alternative surgical robotic system to DVSS, hinotori™ Surgical Robot System (HSRS, Medicaroid, Kobe, Japan), of which the commercial license was issued in August 2020 in Japan [12, 65], and the safety and feasibility of robotic surgery using the HSRS have already been documented in the urological field [66]. Even in the abdominal gastrointestinal and gynecological fields, the national medical insurance coverage has been approved in HSRS in December 2022. This novel robotic system also has a great potential to realize telesurgery. We successfully established a novel telesurgical platform using this surgical robot, and through a leased optic-fiber network, preclinical distal gastrectomy using a porcine model was safely completed [65]. With the maturity of this telesurgical technology, we hope that telesurgical training, teleproctoring and telementoring become more widely available in addition to telesurgery. Further, many companies have accelerated the development of surgical robots, indicating that massive surgical data obtained from robotic surgery, called surgical intelligence [65], attracts developers. By using surgical intelligence and fusion to the artificial intelligence in collaboration with these companies, we sincerely hope further evolution of robotic surgery to enhance the robotic potencies and facilitate improvement in the total outcomes among patients in the near future.

Conclusion

RG for GC is a promising procedure that can reduce postoperative morbidity and improve long-term outcomes. The outcomes of RG are comparable to or better than those of LG. Accordingly, RG might be highly recommended for all patients with GC who fulfill the indication of LG at institutions that meet specific criteria and are approved to claim the National Health Insurance costs for the use of the surgical robots in Japan.

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Declarations

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