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Structured cost analysis of robotic TME resection for rectal cancer: a comparison between the da Vinci Si and Xi in a single surgeon's experience

Luca Morelli[1,2] · Gregorio Di Franco[1] · Valentina Lorenzoni[3] · Simone Guadagni[1] · Matteo Palmeri[1] · Niccolò Furbetta[1] · Desirée Gianardi[1] · Matteo Bianchini[1] · Giovanni Caprili[1] · Franco Mosca[2] · Giuseppe Turchetti[3] · Alfred Cuschieri[4]

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Abstract

Background Robotic-assisted surgery by the da Vinci Si appears to benefit rectal cancer surgery in selected patients, but still has some limitations, one of which is its high costs. Preliminary studies have indicated that the use of the new da Vinci Xi provides some added advantages, but their impact on cost is unknown. The aim of the present study is to compare surgical outcomes and costs of rectal cancer resection by the two platforms, in a single surgeon's experience.

Methods From April 2010 to April 2017, 90 robotic rectal resections were performed, with either the da Vinci Si (Si-RobTME) or the da Vinci Xi (Xi-RobTME). Based on CUSUM analysis, two comparable groups of 40 consecutive Si-RobTME and 40 consecutive Xi-RobTME were obtained from the prospectively collected database and used for the present retrospective comparative study. Data costs were analysed based on the level of experience on the proficiency–gain curve (p–g curve) by the surgeon with each platform.

Results In both groups, two homogeneous phases of the p–g curve were identified: Si1 and Xi1: cases 1–19, Si2 and Xi2: cases 20–40. A significantly higher number of full RAS operations were achieved in the Xi-RobTME group ($p<0.001$). A statistically significant reduction in operating time (OT) during Si2 and Xi2 phase was observed ($p<0.001$), accompanied by reduced overall variable costs (OVC), personnel costs (PC) and consumable costs (CC) ($p<0.001$). All costs were lower in the Xi2 phase compared to Si2 phase: OT 265 versus 290 min ($p=0.052$); OVC 7983 versus 10231.9 ($p=0.009$); PC 1151.6 versus 1260.2 ($p=0.052$), CC 3464.4 versus 3869.7 ($p<0.001$).

Conclusions Our experience confirms a significant reduction of costs with increasing surgeon's experience with both platforms. However, the economic gain was higher with the Xi with shorter OT, reduced PC and CC, in addition to a significantly larger number of cases performed by the fully robotic approach.

Keywords Robotic surgery · TME · Rectal cancer · Structured costs analysis · Da Vinci Xi · Da Vinci Si

Robotic-assisted surgery (RAS) was introduced specifically to overcome the kinematic restrictions imposed on the operating surgeon by conventional laparoscopic surgery. RAS by the da Vinci Surgical system appears to benefit rectal cancer surgery, which in some early series included reduced conversion rates, reduced operative blood loss, greater residual mesorectal fascial integrity rate following pelvic dissection, shorter proficiency–gain curve (p–g curve) and excellent functional results compared with the reported experience by the manual direct laparoscopic approach [1–8]. Nevertheless, even if not all these findings have been reported by the ROLARR trial [9] and by recent meta-analysis [10–12], potential advantages were confirmed in selected patients.

✉ Luca Morelli
luca.morelli@unipi.it

1 General Surgery, Department of Surgery, Translational and New Technologies, University of Pisa, Via Paradisa 2, 56124 Pisa, Italy

2 EndoCAS (Center for Computer Assisted Surgery), University of Pisa, Pisa, Italy

3 Institute of Management, Scuola Superiore Sant'Anna, Pisa, Italy

4 Institute for Medical Science and Technology, University of Dundee, Dundee, Scotland, UK

However, the higher costs of RAS with the da Vinci remain a critical issue, and have prevented its widespread adoption. Additionally, there are other limitations to RAS by the da Vinci Si platform, including the limited flexibility for complete robotic multi-quadrant operations, imposing technical difficulty in achieving complete mobilisation of splenic flexure. Furthermore, if changes in the position of the robot and/or the patient are needed, the robotic system must be undocked to enable safe reposition of the entire platform and re-docking or, alternatively, the surgeon must use a hybrid laparoscopic/robotic approach. The introduction of the new da Vinci Xi platform and its subsequent added use of the da Vinci Table Motion (dVTM) has overcome these limitations. Preliminary studies have indicated that the use of the new da Vinci Xi with the dVTM is associated with a shorter operative time, reduced docking time, and higher full robotic resection rates compared to the previous da Vinci Si [13–21]. The possible impact of these advantages of da Vinci Xi on costs is unknown. Despite several published studies regarding clinical and surgical benefits of robot-assisted colorectal surgery since the introduction of da Vinci Surgical System, to date few studies have reported a structured cost analysis, and none have analysed the possible differences in costs between da Vinci Si and new da Vinci Xi. The aim of this study is to compare surgical parameters and costs of robotic surgery for rectal cancer with the use of da Vinci Si and Xi surgical platforms.

Materials and methods

From April 2010 to April 2017, 90 robotic rectal resections were performed at the General Surgery Unit, University of Pisa, with the da Vinci Si (Si-RobTME) until December 2014, or with the da Vinci Xi (Xi-RobTME) since January 2015.

All the procedures were performed by a single surgeon previously experienced in rectal cancer surgery (> 100 cases), with manual laparoscopic surgery (> 100 cases), and who started his robotic experience with da Vinci Si in November 2009.

For the present study, data on patient outcomes, surgical procedures, and post-operative course were retrieved from a prospectively collected institutional dedicated database. The preoperative work-up included colonoscopy with biopsy, abdominal and trans-rectal ultrasonography, chest radiography, abdomen and pelvic CT scan, and/or magnetic resonance imaging. Patients with clinical stage I cancer (T1-2, N0, M0) were referred for prompt surgical treatment. Patients with clinical stage II–III cancer with T3 and/or N-positive received neoadjuvant chemoradiation (continuous 5-FU infusion/ RT) followed by surgical resection within 8 weeks. T4 lesions were operated through an open approach and excluded from the study as were patients with clinical stage IV cancer (metastatic disease). Obesity (BMI > 30 kg/m^2) or previous abdominal or pelvic surgical procedures were not considered contraindication. An anterior resection of the rectum (ARR) was used for lesions with caudal margin located at least 3 cm above the dentate line. Intersphincteric resection (ISR) with direct manual colo-anal anastomosis was considered for lesions located between 3 and 0.5 cm above the dentate line, while lesions located less than 0.5 cm above the dentate line or with direct sphincter invasion, underwent an abdominoperineal resection (APR). A diverting ileostomy was performed in all ARR and ISR patients. The clinical variables included patient demographics, the American Society of Anaesthesiologists (ASA) scores, body mass index (BMI), neoadjuvant treatment and distance of the tumour from the anal verge were. The perioperative data were operating time (OT), docking time, the use of hybrid or full robotic approach and conversion to open or hand-assisted laparoscopic surgery (HALS). Post-operative data included length of stay and post-operative complication according to the Clavien–Dindo classification [22].

Cost data were obtained from the accounting department of the hospital and added to our institutional prospectively collected database. Costs were expressed in euros and referred to year 2016. Economic data were collected from the accounting department of the hospital. Because the study consisted of a comparison between two successive generations of the same robotic platform, we excluded from the analysis fixed costs (purchase and maintenance). In addition, stapler's costs were excluded because since the introduction of the endo-wristed staplers, they are now available for both systems, they were not available at the time our Si interventions were performed, and so inclusion of these costs in the analysis would have introduced a bias. In fact, for valid representation of consumable costs in current practice, robotic EndoWrist staplers should have been considered for both Si and Xi interventions, and hence do not have any impact on relative costs between the two platforms.

Overall variable costs (OVC) included items related to disposable instruments (consumable costs, CC), operating room personnel (personnel costs, PC), and length of stay (hospital stay costs, HC). Details of resources use and related costs are reported in Appendix (Tables 7, 8 and 9).

Considering OT as an indicator of the proficiency–gain process, the CUSUM method [23] was used to analyse the p–g curve for the two da Vinci systems. This method comprises running the total of the differences between the individual data points and the mean of all data points. First, the cases were ordered chronologically, from the earliest to the last date of surgery. The value of CUSUM operative time (CUSUMOT) of the first case was then obtained as the difference between the OT for the first case and the mean OT for all the cases (mOT). The CUSUMOT of the second case was the CUSUMOT of the previous case added to the difference between the OT of the second case and mOT. The same procedure was repeated for each of the patients except the last one, which was marked as 0.

Based on CUSUM analysis, two comparable groups of 40 consecutive Si-RobTME and 40 consecutive Xi-RobTME were identified.

For the present study, clinical and costs data of these two groups were analysed and compared against the device-specific robotic p–g curve. To compare the variation of costs with the experience, we also matched costs of each phase of the p–g curve of the two groups.

The study was approved by Institutional review board. All patients received an extensive explanation of the procedure and provided informed consent.

Surgery

Surgical technique

For the Si-RobTME group, we used a single-docking full robotic or hybrid technique, based on patient characteristics and intra-operative findings. Main criteria for the hybrid approach included difficulties in exposure of inferior mesenteric vein or splenic flexure; encroachment of the operative field by small bowel loops, visceral obesity and need of multiple changes of table position.

The patients were placed in a modified lithotomy position with a 30° Trendelenburg and a tilt to the right side. In the full robotic technique, a 12-mm optical trocar for the camera was inserted 3 cm to the right and lateral to the umbilicus. An 8-mm trocar for the robotic arm was placed under direct vision at the point of intersection between the mid-clavicular line and the line between the umbilicus and the anterior superior iliac spines on the right side. The other two robotic trocars were inserted in the epigastric region, one on the right either side of the falciform ligament. Another 12-mm trocar in the right flank was inserted for use by the assistant surgeon. In the hybrid technique, the first part of the operation (inferior mesenteric vessel ligation, left colon and splenic flexure mobilisation) was carried out laparoscopically. The trocar for the camera was in the same position as in the full robotic technique, the two operative trocars were epigastric (8 mm) and suprapubic (12 mm), respectively; an 8-mm robotic trocar was placed in the left flank.

The choice for using a hybrid technique was made after placement of the optical trocar and the suprapubic trocar to expose and the evaluate quality of the operative field obtained with changes in the position of the operating table, being made as required. For the robotic step of the intervention (the TME), the cart was positioned to the patient's left side, along an imaginary line between the anterior superior iliac spine and the umbilical scar, at a 60° angle. During this step, the surgeon inserted the 8-mm trocar inside the 12-mm one (trocar in trocar) and another 12-mm trocar was placed in the right flank for the use by the assistant.

In the Xi-RobTME group, patients were placed in a modified lithotomy position with a 30° Trendelenburg and a tilt to the right side. The first 8-mm robotic trocar was placed in the umbilical region, along the right pararectal line. Four trocars were then inserted under vision in an oblique fashion following the classic universal port placement guidelines provided by Intuitive Surgical for 'left lower' abdominal procedures that provides for positioning an 8-mm port in the right iliac fossa, a 12-mm assistant's trocar in the right flank and two 8-mm robotic ports in the periumbilical region and the left hypochondriac space, respectively. However, as previously reported [16–18], we prefer to locate all trocars by 2–5 cm to the right side, to enhance the workspace and facilitate the approach to the splenic flexure with the fourth arm. 'Patient-left' was the selected approach, and the surgical cart was driven to position the green laser crosshairs on the initial endoscope port. After docking, the scope was pointed at the inferior mesenteric pedicle of the sigmoid colon, and function 'targeting' was performed. The boom was then rotated in a clockwise direction to ensure the optimal configuration for dividing the inferior mesenteric pedicles and mobilising the left colon up to the splenic flexure. In our initial experience, we performed a new targeting down to the pelvis with a consequent double docking. However, with increasing experience in performing TME we changed only the targeted anatomical site of the camera from the left side to the pelvis and changed the arm direction and the FLEX of each arm without the necessity to undock the robotic arms and a consequent second docking. The dVTM was used when necessary to obtain the optimal exposure of the operative field.

The colon was exteriorised through a Pfannenstiel suprapubic mini-laparotomy and prepared for the anastomosis, which was performed with a double-stapled end-to-end technique. In case of ISR, the specimen is exteriorised through the anus and a manual colo-anal anastomosis was performed.

Statistical analysis

Categorical variables were reported as number of cases and percentage, while continuous variables were expressed as mean ± (standard deviation) or median [25–75 percentile], depending on their distribution. The Chi-square test and Fisher test were used to compare the distribution of categorical variables. For continuous variables, paired comparisons were made using an independent t-test or Mann–Whitney test, while multiple comparisons were performed by means of an analysis of variance or Kruskal–Wallis test. The

Bonferroni and Mann–Whitney test with Bonferroni correction were considered for post hoc test.

Patient characteristics and perioperative data among Si-RobTME and Xi-RobTME subgroups identified through the CUSUM analysis were compared. Generalised linear models were used to estimate costs associated with the different surgical techniques and phases, adjusting for clinical characteristics and operative parameters. Variables with a *p* value < 0.10 at univariate analysis were included in the multivariable analysis. A *p* value < 0.05 was considered statistically significant. All analyses were performed using R v3.0.2 (R, Vienna, Austria), Stata version 12 (StataCorp, College Station, TX, USA) and SPSS (Statistical Production and Service Solution for Windows, SPSS Inc., Chicago, IL, USA).

Results

The evaluation of the Si-RobTME and Xi-RobTME groups according to p–g curve and based on the CUSUM analysis identified two homogeneous phases in both groups: Si1 and Xi1: cases 1–19, corresponding to the initial p–g curve; Si2 and Xi2: cases 20–40 characterised by stabilisation of OT (Fig. 1).

Demographic characteristics and preoperative condition of the two groups are summarised in Table 1. No significant differences in clinical features between the two groups were identified. Perioperative and pathological data are summarised in Table 2. There was no difference

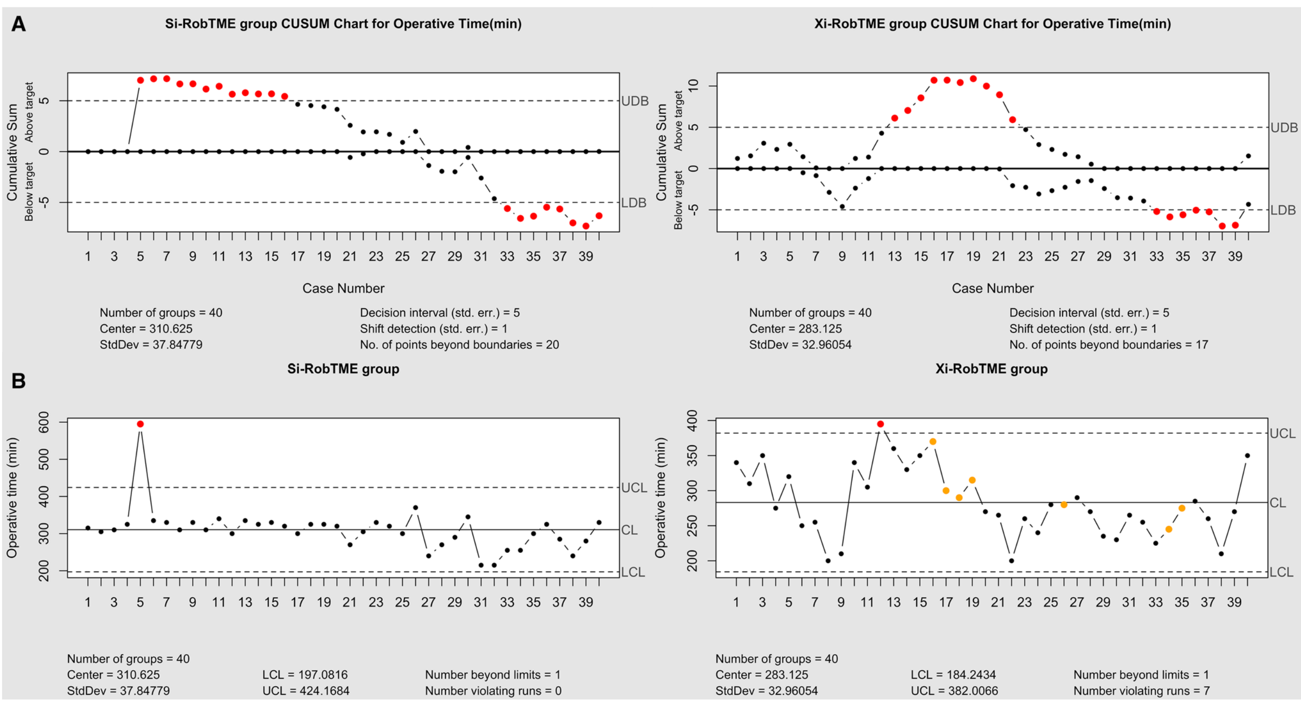

Fig. 1 RobTME operative time (OT): CUSUM chart for OT (Panel **A**) for the Si-RobTME group (left) and the Xi-RobTME group (right); Plot of OT against case number (Panel **B**) for the Si-RobTME group (left) and the Xi-RobTME group (right)

Table 1 Patient characteristics

	Si-RobTME	Xi-RobTME	Overall	*p* value
Mean age, year	69.8 ± 10.8	67.0 ± 11	68.4 ± 11	0.25
Male, *n* (%)	24 (60%)	28 (70%)	52 (65%)	0.88
Mean body mass index, kg/m^2	24.7 ± 3.4 (16.0–31.2)	24.7 ± 3.4 (18.9–35.5)	24.7 ± 3.4	0.94
ASA score, *n* (%)				0.36
ASA I	0	2 (5%)		
ASA II	29 (47.5%)	18 (45%)		
ASA III	21 (52.5%)	20 (50%)		
Neoadjuvant CRT, *n* (%)	18 (45%)	18 (45%)	38 (47.5%)	1
Distance from anal verge, cm	4.0 [1.0–5.0]	4.8 [3.0–10]	4.3 [2.3–7]	0.013

Table 2 Operative and pathological data

	Si-RobTME	Xi-RobTME	*p* value
Surgical procedure, *n* (%)			0.82
ARR	27 (67.5%)	29 (72.5%)	
ISR	6 (15%)	6 (15%)	
APR	7 (17.5%)	5 (12.5%)	
Type of surgical technique			< 0.001
Full robotic	22 (55%)	38 (95%)	
Hybrid technique	17 (42.5%)	0	
Conversion to open approach	1 (2.5%)	2 (5%)	0.56
Mean overall operative time, min	310.6 ± 58.0	283.1 ± 48.9	0.021
Mean docking time, min	22.0 ± 2.5	16.8 ± 3.5	< 0.001
Lymph nodes, *n* (range)	16.7 ± 6.9	18.9 ± 8.2	0.20
Distal resection margin, cm (range)	2.3 ± 1.4	2.4 ± 1.2	0.80
Circumferential resection margin	0	0	1

Table 3 Post-operative and pathological data

	Si-RobTME	Xi-RobTME	*p* value
Median post-operative length of stay, days	9.5 [8–11]	7.0 [5–9]	< 0.001
Overall complications, *n* (%)	14 (17.5%)	10 (12.5%)	0.33
Reintervention, *n* (%)	0	1 (2.5%)	0.31
Mortality	0	0	1

in the surgical procedures performed between the two groups. Mean overall operative time (OT) and mean docking time were significantly shorter in the Xi-RobTME: 283 ± 49 min versus 311 ± 58 min in the Si-RobTME group ($p = 0.025$), with a mean difference of − 27.5 min (95% CI 3.6–51.4), and 16.8 ± 3.5 min in the Xi-RobTME group versus 22.0 ± 2.5 min in the Si-RobTME group ($p < 0.01$), with the mean difference of − 5.3 min (95% CI 3.9–6.6), respectively. There were no conversions to conventional laparoscopy or HALS technique. The procedure was converted to a traditional open approach in one case in the Si-RobTME group for visceral obesity and in two cases in the Xi-RobTME group for the difficulty in identifying planes due to constant oozing from dissection planes because of a coagulopathy in a patient with liver cirrhosis, and for diffuses adhesions due to previous surgery and for anaesthesiologic problems in the second patient. No differences were reported between the two groups with respect to pathological findings. The mean distal resection margin was 2.3 ± 1.4 cm in the Si- RobTME group versus 2.4 ± 1.2 cm in the Xi-RobTME group ($p = 0.73$). A mean of 17 ± 7 lymph nodes per patient were removed in the Si-RobTME group versus 19 ± 8.0 in the Xi-RobTME group ($p = 0.20$). No patients had involvement of circumferential resection margins (≤1 mm) and the quality of the mesorectum, according to Quirke's criteria [24], was 'complete' in all cases.

Post-operative data are summarised in Table 3. Median post-operative length of stay was significantly shorter in the Xi-RobTME group (7 days vs 9.5 days, $p < 0.001$). Post-operative complications occurred in 14 cases in the Si-RobTME group (grade I in 2, grade II in 10, and grade III in 2 on to the Clavien–Dindo Classification) versus 10 cases in the Xi-RobTME group (grade I in 5, grade II in 4, and grade III in 1 according to the Clavien–Dindo Classification) ($p = 0.33$). Four patients in the Si- RobTME group versus one patient in the Xi-RobTME group ($p = 0.36$) experienced transient small bowel obstruction, which resolved with insertion of a 24-F Foley catheter in the ileostomy. One patient in the Xi-RobTME group underwent laparoscopic exploration with closure of the ileostomy on 17th post-operative day for acute abdomen due to perforation of the afferent loop of the ileostomy ($p = 0.99$). No in-hospital mortality was noted in the two groups.

The comparison of patient characteristics and perioperative data by the CUSUM learning phases is summarised in Table 4. There were no differences in patient characteristics in the learning phases. The hybrid approach was used in a higher percentage of patients in the Si1 phase than Si2 phase (11 vs 7 cases) as distinct from no patients in the Xi1 and Xi2 phases ($p < 0.01$).

The comparison of costs incurred by the Si-RobTME and Xi-RobTME groups is summarised in Table 5. Overall median variable costs associated with Xi-RobTME group were significantly lower than with Si-RobTME group: 7687 € versus 10,242 €, respectively ($p < 0.001$). Both costs related to the hospital stay, the cost of consumables and personnel were significantly lower in the Xi-RobTME ($p < 0.001$, $p < 0.001$ and $p = 0.021$, respectively).

When comparing by robotic phases, OVC were lower in Xi1 and Xi2 compared to both Si1 ($p < 0.001$ and $p = 0.002$) and Si2 ($p < 0.001$ and $p = 0.009$). A statistically significant change in OT by phase of robotic experience was detected ($p < 0.001$). Mean OT was significantly lower in Si2 versus Si1 ($p = 0.003$), Xi2 versus Xi1 ($p = 0.009$) also Xi2 versus Si1 ($p < 0.001$) which reflected in PC. The reduction of OT with an increase of robotic experience is accompanied with reduction of PC ($p < 0.001$), but statistically significant differences were present only when comparing the experienced versus the initial phase in both Si ($p = 0.003$) and Xi ($p = 0.009$). A statistically significant reduction in CC by system and robotic phase was detected ($p < 0.001$), and the CC of the Xi2 phase were significantly lower than both Si1 and Si2 phase ($p < 0.001$). Moreover, HC showed a statistically significant difference by both system and robotic phase ($p = 0.001$) with lower cost in

Table 4 Patient characteristics in RobTME group by learning phases: Si1, Si2, Xi1 and Xi2 subgroups

	Si1 (1–19)	Si2 (20–40)	Xi1 (1–19)	Xi2 (20–40)	*p* value Si1 vs Si2	*p* value Si1 vs Xi1	*p* value Si1 vs Xi2	*p* value Si2 vs Xi1	*p* value Si2 vs Xi2	*p* value Xi1 vs Xi2
Age	70.2 ± 10.1	69.4 ± 11.5	66.7 ± 9.5	67.2 ± 12.4	0.81	0.28	0.40	0.43	0.56	0.9
Male gender	9	7	6	6	0.37	0.32	0.22	0.92	0.74	0.84
ASA score										
1	0	0	1	1	0.21	0.51	0.13	0.12	0.52	0.08
2	11	8	12	6						
3	8	13	6	14						
BMI	24.8 ± 3.0	24.5 ± 3.8	25.7 ± 3.7	23.9 ± 2.9	0.75	0.45	0.29	0.32	0.53	0.09
Preoperative CRT	6	12	10	8	0.10	0.19	0.30	0.78	0.22	0.36
Distance from anal verge, cm	4.4 ± 3.1	4.2 ± 3.1	5.4 ± 2.9	5.5 ± 3.8	0.89	0.31	0.33	0.24	0.26	0.94
Type of procedure										
ARR	14	13	13	16	0.69	0.31	0.77	0.40	0.35	0.10
ISR	2	4	5	1						
Miles	3	4	1	4						
Surgical technique										
Hybrid	11	6	0	0	0.08	< 0.001	< 0.001	< 0.001	< 0.001	1
Full robotic	8	14	19	19						
Mean operative time, min	335.0 ± 64.1	288.6 ± 42.2	304.7 ± 50.6	263.6 ± 39.1	0.003	0.246	< 0.001	0.307	0.052	0.009
Median length of hospital stay, days	9	10	6	7	0.26	< 0.001	0.21	< 0.001	0.05	0.50
Post-operative complications	7	7	4	6	0.82	0.21	0.58	0.39	0.74	0.58
Distal margin, cm	2.5. ± 1.6	2.2 ± 1.2	2.4 ± 1.2	2.4 ± 1.2	0.49	0.82	0.85	0.59	0.53	0.95
Lymph nodes	16.7 ± 5.0	16.7 ± 8.3	17.3 ± 8.6	20.3 ± 7.8	0.98	0.80	0.09	0.81	0.15	0.26

Table 5 Comparison of costs between Si-RobTME and Xi-RobTME and the subgroups based on CUSUM analysis

	Median [Q1–Q3]	p value Mann–Whitney
Overall variable costs (OVC) (Euro)		
Robot Si ($n=40$)	10242.4 [9599.4–11216.3]	<0.001
Robot Xi ($n=40$)	7686.8 [6974.5–9187.3]	
Personnel costs (PC) (Euro)		
Robot Si ($n=40$)	1358 [1249.4–1434.1]	0.021
Robot Xi ($n=40$)	1195.1 [1097.3–1379.8]	
Costs of hospital stay (HC) (Euro)		
Robot Si ($n=40$)	4481.2 [3773.7–5188.8]	<0.001
Robot Xi ($n=40$)	3302 [2358.6–4245.4]	
Consumable costs (CC) (Euro)		
Robot Si ($n=40$)	4380.8 [3805.6–4757.8]	<0.001
Robot Xi ($n=40$)	3464.4 [3082.8–3464.4]	

	Median [Q1–Q3]	p value Mann–Whitney	p value Mann–Whitney
Overall variable costs (OVC) (Euro)			
Robot Si phase 1 ($n=19$)	10,445 [9610.2–11798.4]	<0.001	
Robot Si phase 2 ($n=21$)	10231.9 [9566.7–10811.5]		$p=0.421$ vs Si1
Robot Xi phase 1 ($n=19$)	7598.3 [7083.2–8334]		$p<0.001$ vs Si1 $p<0.001$ vs Si2
Robot Xi phase 2 ($n=21$)	7983 [6931.1–10791.7]		$p=0.002$ vs Si1 $p=0.009$ vs Si2 $p=0.592$ vs Xi1
Personnel costs (PC) (Euro)			
Robot Si phase 1 ($n=19$)	1412.3 [1347.2–1434.1]	<0.001	
Robot Si phase 2 ($n=21$)	1260.2 [1108.2–1390.6]		$p=0.003$ vs S1
Robot Xi phase 1 ($n=19$)	1347.2 [1151.6–1521]		$p=0.246$ vs Si1 $p=0.307$ vs Si2
Robot Xi phase 2 ($n=21$)	1151.6 [1043–1216.8]		$p<0.001$ vs Si1 $p=0.052$ vs Si2 $p=0.009$ vs Xi1
Costs of hospital stay (HC) (Euro)			
Robot Si phase 1 ($n=19$)	4245.4 [3773.7–4717.1]	0.001	
Robot Si phase 2 ($n=21$)	4717.1 [3773.7–5660.5]		$p=0.258$ vs Si1
Robot Xi phase 1 ($n=19$)	2830.3 [2358.6–3773.7]		$p<0.001$ vs Si1 $p<0.001$ vs Si2
Robot Xi phase 2 ($n=21$)	3302 [2358.6–6132.2]		$p=0.205$ vs Si1 $p=0.046$ vs Si2 $p=0.503$ vs Xi1
Consumable costs (CC) (Euro)			
Robot Si phase 1 ($n=19$)	4380.8 [4380.8–5324.5]	<0.001	
Robot Si phase 2 ($n=21$)	3869.7 [3741.5–4059.5]		$p<0.001$ vs Si1
Robot Xi phase 1 ($n=19$)	3464.4 [3082.8–3464.4]		$p<0.001$ vs Si1 $p<0.001$ vs Si2
Robot Xi phase 2 ($n=21$)	3464.4 [3464.4–3464.4]		$p<0.001$ vs Si1 $p<0.001$ vs Si2 $p=0.872$ vs Xi1

the Xi1 phase compared to both Si1 and Si2 ($p<0.001$ for both). Only borderline significant difference was found in HC when comparing the Xi2 phase versus the Si2 phase (3302 € vs 4717 €, $p=0.046$).

At multivariable analysis, when adjusting for potential confounding variables, OVC remained significantly lower in Xi2 as compared to both Si1 and Si2 ($p=0.002$ and $p=0.030$, respectively), CC of Xi2 were significantly lower than both phases of Si ($p<0.001$) while PC were lower in Xi2 compared to Si1 and Xi1 ($p < 0.001$ and $p = 0.005$, respectively) (Table 6).

Discussion

The use of da Vinci robot has spread rapidly in colorectal cancer surgery even if its alleged reported advantages over the direct manual laparoscopic approach, including lower conversion rate, shorter p–g curve and improved functional outcomes [1, 3, 6–8, 18], have not been fully confirmed by the recently published randomised clinical trial, and meta-analyses [9–12]. The results of these studies indicate that selected patients, such as obese, men, those with cancer of the lower rectum, and patients operated after receiving preoperative chemoradiotherapy, are those for whom there is high-level evidence of superiority of RAS over direct manual laparoscopic surgery [25–29]. However, the downside of the RAS technique, which remains a critical issue preventing its widespread uptake, relates to its high capital, amortisation, recurrent costs and longer operating time. In the da Vinci Si, the longer operative time is related to limitations intrinsic to this version, including its complicated setup, limited ability to reach all the abdominal quadrants without rearrangement of robotic arms, re-docking and/or repositioning of the surgical cart [18]. The increased costs associated with RAS result not only because of high purchase and maintenance costs of the robot, but also because of high costs of surgical consumables, and the longer operating room times confirmed by several publications [18, 30, 31]. However, one must stress that all the publications refer to experience based on use of the early versions of the da Vinci System including the penultimate one, the Si. The new da Vinci Xi with its innovations, has overcome some of the limitations of the preceding platforms. Indeed, preliminary studies have indicated that the use of the new da Vinci Xi by its technological improvements has the distinct potential to reduce significantly the operating time. Aside from having a shorter docking time, the Xi is more able to cope with multi-quadrant surgery, thereby increasing the full robotic execution of rectal cancer operations, when compared with the da Vinci Si [13, 15–18, 23]. Because these considerations, may translate to reduced costs, we considered the possibility that current reported literature may be exaggerating the increased costs associated with RAS by the da Vinci platform. This consideration has promoted the design and conduct of this cost analysis of a single surgeon's first consecutive 40 robotic rectal resections with the da Vinci Si with the first consecutive 40 robotic rectal resections performed with the da Vinci Xi. In the process, the study also compared the phases of p–g curve of the robotic experience by the two systems. The CUSUM method was used to analyse the p–g curve based on the first 90 cases of robot-assisted rectal cancer resection performed using both the da Vinci platforms. CUSUM p–g curves are used as indicators to detect the acquisition of clinical proficiency in the execution of operations. This method of analysis allowed us to obtain two subgroups that reflect homogeneous phases: the first phase of learning and a second phase of stabilisation of the times. Indeed, given that CUSUM is recognised as a method that provides quality control, it is well suited to analyse changes in parameters characterising productive processes and hence identify "phases" within the process. For that reason, since our objective was to match phases of the process (not patients as it

Table 6 Multivariable regression analysis

	Coef.	SE	p value	95% CI
Overall variable costs (OVC)				
Si1-RobTME vs Xi2-RobTME	2675.5	879.6	0.002	(951.5; 4339.6)
Si2-RobTME vs Xi2-RobTME	1806.4	833.1	0.030	(173.6; 3439.3)
Xi1-RobTME vs Xi2-RobTME	423.0	774.0	0.584	(− 1093.1; 1940.9)
Neoadjuvant therapy	1459.4	645.4	0.024	(194.5; 2724.2)
Complications	480.1	675.9	0.478	(− 844.6; 1804.8)
Intercept	7655.6	589.6	< 0.001	(6500.3; 8811.3)
Consumable costs (CC)				
Si1-RobTME vs Xi2-RobTME	1424.0	151.4	< 0.001	(1127.2; 1720.7)
Si2-RobTME vs Xi2-RobTME	633.6	131.8	< 0.001	(375.3; 891.9)
Xi1-RobTME vs Xi2-RobTME	− 21.6	116.5	0.853	(− 249.9; 206.7)
Dist.lin	− 6.2	11.9	0.604	(− 29.5; 17.2)
Intercept	3396.4	118.4	< 0.001	(3164.3; 3628.5)
Personnel's costs (PC)				
Si1-RobTME vs Xi2-RobTME	307.8	67.4	< 0.001	(175.8; 439.9)
Si2-RobTME vs Xi2-RobTME	83.8	60.8	0.168	(− 35.4; 203.0)
Xi1-RobTME vs Xi2-RobTME	177.4	63.5	0.005	(52.9; 302.0)
Dist.lin	− 1.5	1.9	0.420	(− 5.1;2.1)
Intercept	1183.5	62.6	< 0.001	(1060.1; 1306.3)

is common in clinical studies), this method was used to identify (and match) phases of the learning process. It has several advantages, including independence on sample size, effectiveness in detecting small changes, its ability to allow for a continuous analysis in time and rapid evaluation of data [23]. Many authors agree that the p–g curve embraces different phases in which surgeons first gain robotic skills and then, with increasing familiarity with the new technique and new technology, the surgeon is able to decrease in OT and hospital costs over time [23, 32–34]. In changing from da Vinci Si to da Vinci Xi, the surgeon must deal with the novel aspects of the new platform such as different trocar placements, robotic cart position, new functions (pointing, targeting, camera hopping, etc.), new docking system and robotic arms regulation [18], even if the surgeon is already expert in both laparoscopic and robotic laparoscopic rectal resections. We have reported previously that after the first two cases of rectal resection performed with the da Vinci Xi, in which the 'classic' Universal Port Placement Guidelines provided by Intuitive Surgical for 'left lower' abdominal procedures was used, a modification of the trocar placement was used [16], which facilitates the approach to the transverse colon and splenic flexure by increasing the manipulation space, without causing difficulties during the pelvic phase, only possible by the intrinsic flexibility of the da Vinci Xi [18]. With further experience, we changed our surgical technique of robotic rectal resection with da Vinci Xi further by replacing the double targeting technique during the first phase, consisting of initial targeting the mesenteric vein isolation and splenic flexure mobilisation, followed by the second targeting the pelvis, to a single targeting technique modifying only the FLEX of the robotic arm for the two phases of the operation with a further reduction of the operating time. All these modifications are features of a proficiency–gain phase for the first Xi cases.

Our costs analysis revealed a significant decrease of OVC with surgeon's experience. The impact on reduction of costs with surgeon's experience is in accordance with data reported in our previous costs analysis comparing laparoscopic rectal resection with robotic rectal resection performed with the da Vinci Si [23]. Although the documented cost reduction is likely to be multifactorial, the optimisation of instrument use and reduction of OT are two major contributors [23]. A further decrease of costs is clearly related to the shift from the Si to the Xi technology and is characterised by the significant reduction in OT, PC and CC associated with use of the new da Vinci Xi. However, the significant reduction of HS with the da Vinci Xi versus Si-RobTME must be treated with caution, as the data on HS are subject to bias. Thus, it can be explained by the difference in post-operative complications in the two groups or could be secondary to an enhanced recovery protocol in Xi-RobTME group. Additionally, because the Si-RobTME group included patients treated during our early experience with the robotic surgery, a more cautious policy may have been used for discharging patients from hospital [35].

In contrast, we believe that the reduction of OT and the improved ability to perform the procedure by a fully robotic approach offered by the da Vinci Xi are the two main factors influencing the reduction of costs. Indeed, the technological improvements offered by the da Vinci Xi, i.e. increased flexibility and range of motion of the cart and arms, as well as the ability to obtain the excellent exposure of the operative field without repositioning the patient have contributed to shorter operative and console times and the increased rate of fully robotic resections, well documented in the literature [15–17, 19, 20]. The reduction of the OT has influenced in turn reduction in PC because of a lower operative room (OR) hours. Our observation is in line with those recently report by Patel et al. in urology, that revealed in a comparative study with the da Vinci Si, that the da Vinci Xi robotic nephroureterectomy reduced overall HC due to the reduction of anaesthesia and OR cost [36]. The significant reduction of the CC was mainly due to the higher number of full robotic operations achieved with the da Vinci Xi, because it avoids the use of laparoscopic instruments and devices for the laparoscopic phase used in the hybrid technique.

The main limitations of the present study are its retrospective nature and the small sample size, which preclude definitive conclusions. In addition, as the study is based on experience of a single surgeon, its more general application to robotic-assisted rectal cancer surgery is limited without further collaborative studies. A further limitation imposed by the study design was the exclusion of capital costs and amortisation from the analysis. Hence, we acknowledge that their inclusion would be necessary for a complete assessment of overall costs.

However, the present study, the first to compare costs incurred using the new da Vinci Xi with its predecessor has produced cost differences, some of which are significant, but obviously further larger structured cost analysis studies are needed to confirm the cost minimisation by the da Vinci Xi.

Perhaps, the most important take home message from the present study is to highlight that the current economic evaluation on robotic-assisted surgery that has provided unfavourable cost comparisons between robotic-assisted surgery and manual direct laparoscopy surgery, has all been based on studies performed with the da Vinci Si, and further compounded by comparing expert laparoscopic with novice robotic surgeons. The use of the new robot Xi, with case series being performed by expert robotic surgeons, represents a totally different proposition, requiring careful objective re-evaluation of relative costs between the two surgical approaches.

Conclusions

In conclusion, the similar p–g curve for both groups were likely due to a 'proficiency–gain effect' related mainly to the use of a new robotic technology, and not to the surgical operation itself. In taking up the new technology, the surgeon initially becomes familiar with new trocar placements, robotic cart position, new functions (pointing, targeting, camera hopping, etc.), new docking system and robotic arms regulation. Beyond this initial familiarisation stage, the study has documented a significant decrease of costs with increasing surgeon's experience, and change from the Si to the Xi da Vinci, which is characterised by shorter OT, PC and reduction in the CC, together with enabling a higher number of full robotic operations than previously possible with the da Vinci Si. However, the important limitation of robotic TME rectal resection for cancer, and of robotic surgery in general that persists relates to the high fixed costs. Efforts to reduce these are essential for both long-term financial sustainability of robotic surgery and increased uptake of RAS needed to improve the outcome of patients undergoing curative surgical excision of solid cancers resulting from technical advantages offered by the robotic platforms.

Compliance with ethical standards

Disclosures Prof Luca Morelli, Dr Gregorio Di Franco, Dr Valentina Lorenzoni, Dr Simone Guadagni, Dr Matteo Palmeri, Dr Niccolò Furbetta, Dr Desirèe Gianardi, Dr Mattero Bianchini, Dr Giovanni Caprili, Prof Franco Mosca, Prof Giuseppe Turchetti and Prof Alfred Cuschieri have no conflicts of interest or financial ties to disclose.

Appendix

See Tables 7, 8 and 9.

Table 7 Resource use and costs in Xi- and Si- robotic rectal resection: personnel and hospital stay

Personnel group	Unit cost (€/h)	Number of figures
Surgeon	63.77	2
Staff anaesthesiologist	56.77	1
Anaesthesiology technologist	25.12	1
Surgical nurse	25.01	1
Surgical technologist	26.3	1
Nurse assistant	19.01	1
	Unit cost (€/day)	Number of figures
Hospital stay	471.71	–

Si-RobTME and Xi-RobTME intervention involve the same type and number of personnel

Table 8 Consumable use and costs for a Si-RobTME rectal resection by type of intervention

	Unit cost (€)	ARR		APR		IRS	
		Quantity	Overall CC (€)	Quantity	Overall CC (€)	Quantity	Overall CC (€)
Instrument arm drape	131.6	3	394.7	3	394.7	3	394.7
Camera arm drape	122.5	1	122.5	1	122.5	1	122.5
Camera head drape	113.7	1	113.7	1	113.7	1	113.7
Trocar	56.1	2	112.2	2	112.2	2	112.2
Cannula reducer	45.5	2	91.1	2	91.1	2	91.1
Veress needle	6.1	1	6.1	1	6.1	1	6.1
Circular stapler CDH 29	495.0	1	495.0	0	0.0	0	0.0
Gel port	350.0	0	0.0	0	0.0	0	0.0
Surgical drape	16.0	1	16.0	0	0.0	0	0.0
Lone-star retractor system	189.7	0	0.0	0	0.0	1	189.7
Hem-o-Lok polymer ligation system—clip large	8.1	2	16.1	2	16.1	2	16.1
Fenestrated bipolar forceps	784.7	1	784.7	1	784.7	1	784.7
Hot Shears™ monopolar curved scissors	928.3	1	928.3	1	928.3	1	928.3
Tip cover accessory	58.7	1	58.7	1	58.7	1	58.7
Cadiere/ProGrasp forceps	608.5	1	608.5	1	608.5	1	608.5
Overall costs	–	–	3747.6	–	3236.6	–	3426.3

For Si-RobTME in case hybrid interventions additional costs of about 640.7 € (related to Ultracision dissector and cover for video camera) need to be considered; while for interventions in the first Si-RobTME phase additional costs of about 1905.8 € (related to robotic hook and single-use-robotic ultracision)

Table 9 Consumable use and costs for a Xi-RobTME rectal resection by type of intervention

	Unit cost (€)	ARR		APR		IRS	
		Quantity	Overall CC (€)	Quantity	Overall CC (€)	Quantity	Overall CC (€)
Instrument arm drape	131.6	4	526.2	4	526.2	4	526.2
Camera arm drape	122.5	0	0.0	0	0.0	0	0.0
Camera head drape	113.7	0	0.0	0	0.0	0	0.0
Column drape	62.8	1	62.8	1	62.8	1	62.8
Veress needle	6.2	1	6.2	1	6.2	1	6.2
Circular stapler CDH 29	495.0	1	495.0	0	0.0	0	0.0
3M wound edge protector	2.2	1	2.2	0	0.0	0	0.0
Lone-star retractor system	115.6	0	0.0	0	0.0	1	115.6
Hem-o-Lok polymer ligation system—clip large	8.1	2.5	20.2	2.5	20.2	2.5	20.2
Fenestrated bipolar forceps	784.7	1	784.7	1	784.7	1	784.7
Hot Shears™ monopolar curved scissors	928.3	1	928.3	1	928.3	1	928.3
Tip cover accessory	58.7	1	58.7	1	58.7	1	58.7
Cadiere forceps	580.2	1	580.2	1	580.2	1	580.2
Overall costs	–	–	3464.4	–	2967.2	–	3082.8

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