



Evaluation of the economic impact of the robotic approach in major and postero-superior segment liver resections: a multicenter retrospective analysis

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Background: Economic impact of robotic liver surgery (RLS) is still a debated issue due to the heterogeneity of liver resections considered and the lack of a rigorous methodology. Therefore, the aim of this study is to perform a time-driven activity-based costing (TD-ABC) comparing the costs of RLS, laparoscopic liver surgery (LLS) and open liver surgery (OLS) in the context of complex liver resections and to compare short term perioperative outcomes.

Methods: The institutional databases of two Italian high volume hepatobiliary centres were retrospectively reviewed from February 2021 to April 2022. Patients submitted to major hepatectomies or postero-superior liver resections were selected and divided into three groups according to the approach scheduled (RLS, LLS and OLS) and compared. Major contributors of perioperative expenses were calculated using the TD-ABC model and accurately quantifying each unit resource consumed per patient and the time spent performing each activity. A primary intention-to-treat analysis (ITT-A) including conversions in the RLS and LLS groups was performed.

Results: Forty-seven RLS, 101 LLS and 124 OLS were collected. LLS and RLS showed reduced blood loss, morbidity, mortality and hospital stay compared with open. A trend towards reduced conversion rate in RLS compared to LLS was registered. Total costs associated with RLS were estimated at €10,637 *vs.* €9,543 for LLS and *vs.* €13,960 for OLS. The higher intraoperative costs associated with RLS (+153.3% *vs.* OLS and +148.2% *vs.* LLS, $P < 0.001$), primarily related to surgical equipment expenses, were slightly offset by the postoperative savings (-56.0% *vs.* OLS and -29.4% *vs.* LLS, $P < 0.001$) resulting from significantly reduced hospital stays.

Conclusions: RLS offers economic advantages over OLS, as initial higher costs are offset by better perioperative outcomes. The evolving robotic marketplace is expected to drive down RLS costs, promoting widespread adoption in minimally invasive procedures. Despite its higher costs than LLS, RLS's ability to enhance minimally invasive feasibility makes it a preferred choice for complex cases, reducing the need for conversions.

Keywords: Economic evaluation; minimally-invasive liver surgery; robotic liver surgery (RLS); laparoscopic liver surgery (LLS); time-driven activity-based costing (TD-ABC)

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Introduction

In the expanding era of minimally invasive surgery, the robot-assisted technique is emerging as an important contribution in the field of hepatobiliary surgery (1). The role of robotic liver surgery (RLS) as a valid alternative to laparoscopy is documented and there is a growing body of evidence regarding its feasibility and safety (2). However, the precise role of the robotic approach in the whole scenario of liver surgery is not fully determined (3). Similarly to laparoscopy, RLS provides superior peri-operative outcomes in comparison to the open approach, including lower blood loss, decreased morbidity, shortened length of hospitalization and earlier return to daily activities (4). Thereby, RLS has shown adequacy for the treatment of malignant diseases, even providing advantages to achieve

the oncological radicality while preserving the benefits of minimally invasiveness (5).

Since its introduction, robotic technology has been designed and has progressively evolved to face laparoscopic setbacks (6). While a major drawback of laparoscopic surgery is reduced dexterity with poor extent of motions and difficulty performing complex tasks such as suturing or vascular resections (7), the robotic platform has provided instruments with high degrees of freedom, a stable three-dimensional (3D) vision, algorithms suppressing the hand tremor, and enhanced ergonomics for the console surgeon (8-10). It is suggested that the robotic approach may facilitate more difficult liver resections due to freely articulating and angling instruments, such as resections of the postero-superior segments (namely, segments 1, 7, 8, and 4a), major liver hepatectomies (defined as three or more Couinaud segments) and those requiring extensive hilar dissection or biliary reconstructions, thus reducing the risk of conversion and conversion related risks of morbidity and mortality (11-14).

Despite these technological advantages, the robotic technique accounts for less than 8% of all minimally invasive hepatectomies. Among factors limiting its spread, the most mentioned in literature is cost. In a recent survey conducted across 103 European liver centres to assess the adoption of the robotic approach, respondents identified uncertain effect on financial expenditure as the predominant obstacle, with 80% citing it as a significant disadvantage (15).

Previous analysis on costs of RLS has yielded controversial results about the balance between costs and benefits deriving from its implementation. On the one side, the techniques used to calculate costs vary greatly, potentially impacting the final outcome (16-21). Additionally, the existing literature on this topic mostly compare broad categories of liver resections without considering the initial purchase costs of the robotic platform, which is associated with a significant increase in hospital resource utilization. As such the actual knowledge is not sufficient to draw firm conclusions on this topic.

Considering these premises, the aim of the study is to perform a rigorous economic analysis, through a time-driven activity-based costing (TD-ABC) model, in order to compare open, laparoscopic and robotic approaches

Highlight box

Key findings

- Robotic liver surgery (RLS) is associated with higher intraoperative costs, primarily related to surgical equipment expenses. However, these were slightly offset by the postoperative savings resulting from significantly reduced length of stay.

What is known and what is new?

- RLS has gained prominence in minimally invasive hepatobiliary surgery, accounting for less than 8% of in Europe, with financial considerations being a limiting factor. Prior studies have reported conflicting results on the cost-effectiveness of RLS primarily due to variations in cost calculation methods.
- This study contributes comprehensive economic analysis, based on real-world evidence from Italian centers, utilizes a time-driven activity-based costing model, revealing RLS's potential cost-effectiveness despite higher intraoperative costs.

What is the implication, and what should change now?

- Insights into perioperative outcomes, and costs associated with open, laparoscopic, and robotic liver surgeries aid informed decision-making in clinical practice. Hospitals and healthcare systems should evaluate the cost implications of adopting RLS, considering both intraoperative and postoperative expenses. Anticipated reductions in acquisition costs and increased proficiency in RLS are expected to contribute to its favorability. Continuous efforts in training and protocol development are needed for a balanced assessment of clinical benefits, economic implications, and ongoing advancements in the field.

using real world data coming from two high volume Italian centres with well-established programs of liver resections. Provided the overall clinical benefit compared with laparoscopy already described, the analysis is restricted to procedures with high degree of technical complexity. In particular, in a prior investigation, Cipriani *et al.* conducted a comparative analysis of laparoscopic and robotic liver surgeries, stratifying the resections based on varying levels of difficulty. The findings support the theoretical advantages of robotics particularly in facilitating postero-superior and major liver resections (2). The result of this study prompted the authors to specifically concentrate the current analysis on this specific setting to address the issue of comparative costs of open *vs.* laparoscopy *vs.* robotic approach as a primary endpoint.

Secondary endpoint is the comparative evaluation of short-term clinical outcomes and the analysis of real-life allocation of cases to each available approach (i.e., open, laparoscopic, robotic).

Methods

Study design

For the present investigation, the study population was identified from prospectively maintained databases at two Italian high-volume hepatobiliary centres. Consecutive liver resections performed for primary or secondary liver tumours and benign conditions were identified by retrospectively reviewing the database of surgical activity performed at San Raffaele Hospital (Milan, Italy) and at Gemelli Hospital (Rome, Italy). Major hepatectomies and postero-superior liver resections performed from February 2021 to April 2022 with open, laparoscopic, or robotic approaches constituted the study population. According to the Brisbane 2000 Nomenclature, major liver resections were defined as the resection of three or more liver segments (22). Postero-superior segments were defined following the Couinaud segmental anatomy of the liver (segments 1, 7, 8, and 4a) (23). The analysis was restricted to a 1-year time frame to reduce the influence of major variations in the inflation power over time on final results and to consider a homogeneous pool of procedures carried out with a standardized technique and perioperative management.

Exclusion criteria were the following:

- (I) Age under 18;
- (II) Non elective admission;
- (III) Two stage hepatectomies, including Associating

Liver Partitioning and Portal vein ligation for Staged hepatectomy (ALPPS);

- (IV) Cyst unroofing and pericystectomies.

The type of procedure scheduled (i.e., major hepatectomies and postero-superior liver resections) was decided without adjustments based on the surgical approach (open/laparoscopic/robotic). The following disease characteristics were considered as exclusion criteria for a minimally invasive (laparoscopic or robotic) approach over the entire period:

- (I) Lesions strictly adjacent or infiltrating the hepatocaval confluence or inferior vena cava;
- (II) Lesions with presumed infiltration of the hepatic vein of the future liver remnant;
- (III) Patients with portal vein thrombosis requiring portal vein thrombectomy;
- (IV) Patients with more than 10 liver lesions and/or requiring more than 10 resection areas;
- (V) Anaesthesiologic contraindications to pneumoperitoneum (e.g., severe cardio-pulmonary disease).

The bi-institutional cohort of liver resections was stratified into three study groups according to the approach defined by the surgical team: open, laparoscopic, and robotic. With regard to the occurrence of conversion to an open procedure during laparoscopic or robotic resections, the primary analysis relied on the intention-to-treat analysis (ITT-A; i.e., retaining the converted cases in the laparoscopic and in the robotic group) to reflect at best the real clinical setting, where conversion is required in a variable proportion of patients. The reasons for conversion have been classified in: technical difficulties, oncological radicality, intraoperative hemorrhage, anesthesiologic issues, adhesions due to previous surgery and injury to adjacent organs.

The study population derived from the Italian “I GoMILS” registry. Ethical approval for the registry was granted by the Ethics Committee of the promoting center and shared among the participants (IGOMILS-OSR of March 6, 2014—available at: <https://www.cr-technology.com/igomils/eclinical/website/documents.aspx>). Written consent from subjects was waived.

This study adheres to the principles outlined in the Declaration of Helsinki (as revised in 2013).

Preoperative and intraoperative management

Prior to surgery, a standard staging was performed and this

included routine blood tests, computed tomography of the abdomen with triphasic liver contrast enhancement, and/or liver specific contrast magnetic resonance imaging. All cases underwent a comprehensive evaluation in formal weekly institutional multidisciplinary meetings, involving the surgical team, pathologist, radiologist, oncologist, anaesthetists, and navigator nurse. These meetings facilitated the development of an overall operative plan, considering patient characteristics, comorbidities, and the pathological, anatomical, and radiological features of the disease, guiding the selection of the surgical approach. Strict adherence to recent exclusion criteria for minimally-invasive liver surgery was maintained. The criteria and process for selecting patients for each surgical approach were not affected by patients' treatment preferences (24).

Robotic approach: The Da Vinci[®] Xi robotic platform (Intuitive Surgical, USA) was utilized in all robotic cases. The patient received general anaesthesia and the first surgeon operated at the console while the assistant was standing between the patient's legs. A laparoscopic 10 mm trocar was positioned in an infraumbilical right position, and pneumoperitoneum was induced. Four robotic trocars were placed following a standardized configuration based on the planned resection. The standard robotic instrumentation for liver resections included: prograsp forceps, Maryland bipolar forceps, and monopolar scissors. Robo-Lap approach was used in selected cases to address the task of parenchymal transection (25). Specifically, 55.3% of patients who underwent RLS were performed with Robo-Lap approach. Both the referring centers object of the analysis used the Misonix[®] device.

Laparoscopic approach: with the patient under general anaesthesia, the surgical team followed the French position with the first surgeon positioned between the patient's legs and the first and the second assistant on the left and on the right side of the patient, respectively. As described in previous reports, five ports were placed in an inverted J-shaped standard configuration (26,27). Parenchymal transection was performed by combining ultrasonic dissector and bipolar forceps as described in details in previous works (28).

Open approach: with the patient under general anaesthesia, a xipho-supraumbilical incision extending to the right subcostal area was made in subjects undergoing laparotomy. During the procedure, intraoperative ultrasound was routinely performed to assess the anatomy of the liver, confirm resectability and evaluate the relationship between the lesion and the main vascular and biliary

structures within the liver parenchyma.

Lastly, regardless of the approach employed, primary extraparenchymal vascular control was always achieved before transection (Pringle maneuver).

Perioperative endpoints and definitions

Open, laparoscopic, and robotic liver resections were compared for the assessment of feasibility and efficacy, following parameters of short-term outcomes.

Intraoperative outcomes included: operative time (minutes), blood loss (mL), red blood cells and fresh frozen plasma (FFP) transfusions and amount (mL), surgical radicality rate (R0), conversion rate (for laparoscopic and open groups). Operative time was calculated as the time between laparotomy and skin suture for the open group and the time between pneumoperitoneum induction and port-site closure for minimally invasive groups (laparoscopic and robotic groups). Intraoperative blood loss was measured by subtraction. Complications were classified according to the Clavien-Dindo classification (29).

Postoperative outcomes included in-hospital mortality and morbidity rate; type and severity of complications (general and liver-specific), reoperation rate, blood products (red cells and FFP), transfusions and amount (mL), postoperative investigations (radiological/endoscopic), administration of medical agents, postoperative radiological/endoscopic procedures (including radio-guided drainage of collections, ascites or pleural effusion; endoscopic retrograde cholangiopancreatography ± insertion of biliary stent), length of stay (days). Specific definitions of liver complications were adopted: liver failure as an increased international normalized ratio and concomitant hyperbilirubinemia on or after postoperative day (POD) 5 (30); ascites as an abdominal drainage above 10 mL/kg body weight/day after POD 3 (31); bile leak as a bilirubin concentration in the drainage above three-fold of serum total bilirubin on or after POD 3, or the need for radiologic or operative intervention from a biliary collection or bile peritonitis (32). Resection margins were defined into R0 and R1 (33).

Economic analysis

The economic analysis took into consideration contributors of hospital costs as follows:

- ❖ Intraoperative expenses: including operating room charges per minute, equips (surgeons, anaesthetists,

nurses) per minute, disposable devices per piece, sterilization/maintenance of reusable devices, anaesthetic medical agents per posological unit, blood transfusion requirements (mL), histopathological exam (frozen sections and final) per service.

- ❖ Postoperative expenses: including blood transfusion requirement (mL), antibiotic therapy per posological unit, postoperative imaging per service, any reintervention (radiological and/or endoscopic and/or surgical) per service, and ward/intensive care unit (ICU) bed per night.

Investigations and clinical evaluations in the setting of the preoperative assessments and indirect costs were excluded from the analysis.

Intraoperative and postoperative expenses were calculated using the TD-ABC methodology described by Kaplan and Anderson at the Harvard Business School, considered the gold standard for cost determination studies (34). Briefly, TD-ABC examines actual operational processes across the entire care pathway and has been shown to be more accurate in cost analyses compared to traditional accounting methods. TD-ABC provides patient specific data on the cost of personnel and supply resources consumed by each patient. Furthermore, provided the temporal analysis of TD-ABC, it allows to estimate the unit cost of supplying capacity (e.g., cost per minute of a surgeon's time) and utilizes time equations to estimate the time spent performing each activity (35). This technique is based on the concept that the performance of a service consumes activities which then consume resources. TD-ABC attempts to assign costs to each of these activities and/or resources so that total costs can be better understood and managed. It differs from traditional accounting in that it is based on the activities that drive costs. This allows one to manage processes by having clearer understanding of what drives costs and how increases in efficiency affect costs. Many quality improvement techniques also break process into discrete units. This is done to standardize processes, improve them, and eliminate unnecessary variability (36). Process maps were used to determine TD-ABC for all cases included in the study. Indirect costs were excluded from the analysis.

Personnel costs were computed using salary data obtained from the national collective labor agreement. By dividing the calculated cost by the capacity in minutes, a per-minute capacity cost rate was provided for each professional involved in the operating room. The capacity

cost rate was multiplied by the mean operative time in order to define the total cost.

Costs associated with disposable and reusable devices were determined using the regional calls for tenders; postoperative investigations costs were obtained from the Italian national outpatient tariffs; the antibiotic therapy costs were extrapolated from the Italian medicine agency transparency lists using an average posology from the summary of product characteristics (SPCs).

Costs of sterilization of reusable devices, anaesthetic medical agents, histopathological exam, and ward/ICU bed per night were identified by an extensive review of the scientific literature (37-40).

Regarding the blood products transfusion costs, calculations were determined according to expert opinions from the recruiting centers. A specific TD-ABC model, developed from the input received of physicians operating in transfusion centers, has been established in order to assign value to staff time, disposables, hemovigilance, tests, and transportation expenses.

The cost of conversion for the two minimally invasive groups was expressed as an additional cost, calculated as a percentage. This was determined by taking the ratio between the mean cost of converted resections to the mean cost of completed resections.

A comparative sub-analysis of intra-, postoperative and total costs was performed for patients who had no postoperative complications.

Data costs inputs were extracted and audited by an expert in health economics from the Postgraduate School of Health Economics and Management (ALTEMS) of Università Cattolica del Sacro Cuore, Rome.

All costs calculations were performed in Euro and results are expressed in Euro.

Statistics

Demographic data, surgical procedures and the postoperative course were analysed. Before the comparison, the homogeneity of the sample was tested for the baseline characteristics. Variables used were: age (years); gender (male/female); ASA score (1-4); diagnosis (benign/malignant); size of the largest lesion (mm); background liver (healthy/steatosis/fibrosis-cirrhosis); liver function according to the Child-Pugh grade (A/B); previous abdominal surgery (yes/no); extent of the liver resection (minor/major); type of hepatectomy (major hepatectomy/postero-superior sectionectomy); associated hilar

lymphadenectomy (LND) (yes/no); associated biliary reconstruction (yes/no). Only those patients with completed perioperative data available at the end of recruitment were selected for comparison.

For continuous variables, median values with interquartile ranges were considered since their distribution was skewed (Shapiro-Wilk test); categorical variables were expressed as absolute values and proportions. Continuous variables were compared using the non-parametric Kruskal-Wallis test; categorical variables were compared through the chi-square test. Continuous variables related costs are expressed as mean with standard deviation, absolute difference, percentage difference, and are compared using the analysis of variance (ANOVA). Statistical significance was set at $P < 0.05$ and hypothesis tests were two-sided. Statistical analysis was performed using Jamovi software (version 2.3.21 for Windows).

Results

Patient characteristics

Two hundred and seventy-two patients within the study period were included in the analysis. There were 124 (46%) patients who had open liver surgery (OLS), 101 (37%) patients who had laparoscopic liver surgery (LLS), and 47 (17%) patients who underwent RLS.

Comorbidity rate was similar among all three cohorts, as demonstrated by the same patient's stratification based on the American Society of Anaesthesiologists score.

Indications for surgery were dissimilar: a higher proportion of benign disease was present in the RLS group whereas malignant disease were more frequent in the other two groups (76.60% for RLS *vs.* 92.08% for LLS *vs.* 95.97% for OLS, $P < 0.001$). Liver lesions robotically approached have shown larger median size than the other two groups (40 *vs.* 30 mm for LLS *vs.* 30 mm for OLS, $P < 0.001$). Even though a statistically different distribution of the background liver was observed, Child-Pugh grade did not differ among the three groups. The rate of previous abdominal surgery was significantly higher in the RLS group (78.72% *vs.* 56.44% for LLS *vs.* 50% for OLS, $P = 0.003$).

In terms of the type of hepatectomy the OLS and the RLS groups had more major hepatectomies than the LLS group, and inversely the LLS group had more postero-superior liver resections than the other two groups ($P = 0.018$). However, the proportion of hilar lymphadenectomies and biliary reconstructions did not differ between groups. Complete baseline characteristics are

shown in *Table 1*.

Perioperative outcomes

Perioperative outcomes are depicted in *Table 2*.

Patients in the RLS group had significantly longer operative time than those in the LLS and OLS groups ($P < 0.001$). The two minimally invasive groups were associated with lower intraoperative blood loss as compared to the open ($P < 0.001$). There were no differences between the three groups in RBC transfusion rate ($P = 0.061$), however the OLS group received more FFP transfusions comparing with the other two ($P = 0.014$). Significantly higher R0 resection rate was detected in the LLS and RLS groups than in the OLS group (97.03% for LLS *vs.* 91.49% for RLS *vs.* 81.45% for OLS, $P < 0.001$). There were no significant differences observed between the two minimally invasive groups regarding the rate of conversion. However, patients in the RLS group showed a conversion rate of 17.02% compared to 26.73% in the laparoscopic group. Referring to the reason for conversion no patients have been converted for injury to adjacent organs. The main reason of conversion in both the minimally invasive groups has been "technical difficulties". More patient in the laparoscopic group have been converted due to oncological radicality, but there is not a statistically significant difference between the two groups.

Although postoperative morbidity being similar comparing the three groups ($P = 0.259$), the OLS group exhibited significantly higher severe complications when severity was taken into account ($P = 0.006$). In particular, the LLS and the RLS groups experienced lower liver-specific complications (14.85% for LLS *vs.* 17.02% for RLS *vs.* 29.84% for OLS, $P = 0.018$) and no ascites occurred in the RLS group ($P = 0.002$). Moreover, the RLS group was associated with lower mortality rate ($P < 0.001$) and shorter postoperative total stay ($P < 0.001$). However, analysing the sub-population of patients with no postoperative complications, the median length of stay became similar among the three groups (4.5 days for the OLS group, 4 days for the two minimally invasive groups). No significant differences were found in terms of the need for radiological investigations, antibiotics and blood product transfusions among the groups.

Costs analysis

As reported in *Table 3*, for RLS the expenses related to

Table 1 Baseline characteristics and type of liver resections performed in the OLS, LLS and RLS groups

Patient baseline characteristics	OLS (n=124)	LLS (n=101)	RLS (n=47)	P value
Diagnosis				
Benign	5 (4.03)	8 (7.92)	11 (23.40)	<0.001
Adenoma	1 (0.81)	0	3 (6.38)	0.008
Haemangioma	3 (2.42)	4 (3.96)	2 (4.26)	0.751
Other	2 (1.61)	4 (3.96)	6 (12.77)	0.115
Malignant	119 (95.97)	93 (92.08)	36 (76.60)	<0.001
HCC	9 (7.26)	18 (17.82)	10 (21.28)	0.017
iCCA	17 (13.71)	8 (7.92)	9 (19.15)	0.135
pCCA	14 (11.29)	6 (5.94)	2 (4.26)	0.195
CRLM	73 (58.87)	57 (56.44)	9 (19.15)	<0.001
Other	6 (4.84)	4 (3.96)	6 (12.77)	0.085
Age (years)	66 (56–71)	67 (57–73)	66 (59–75)	0.650
Gender				
Female	47 (37.90)	41 (40.59)	22 (46.81)	0.570
Male	77 (62.10)	60 (59.41)	25 (53.19)	
ASA score				0.331
ASA 1	10 (8.06)	7 (6.93)	5 (10.64)	
ASA 2	60 (48.39)	59 (58.42)	25 (53.19)	
ASA 3	48 (38.71)	35 (34.65)	15 (31.91)	
ASA 4	6 (4.84)	0	2 (4.26)	
Size of the biggest lesion (mm)	30 (17–56)	30 (20–45)	40 (25–66)	<0.001
Background liver				0.002
Healthy	109 (87.90)	81 (80.20)	30 (63.83)	
Steatosis	4 (3.23)	9 (8.91)	10 (21.28)	
Fibrosis/cirrhosis	11 (8.87)	11 (10.89)	7 (14.89)	
Child-Pugh grade				0.090
Child-Pugh A	124 (100.00)	101 (100.00)	46 (97.87)	
Child-Pugh B	0	0	1 (2.13)	
Previous abdominal surgery	62 (50.00)	57 (56.44)	37 (78.72)	0.003
Type of the hepatectomy				0.018
Major hepatectomy	56 (45.16)	28 (27.72)	21(44.68)	
Postero-superior sectionectomy	68 (54.84)	73 (72.28)	26 (55.32)	
Associated hilar lymphadenectomy	22 (17.74)	12 (11.88)	11 (23.40)	0.190
Associated biliary reconstruction	12 (9.68)	6 (5.94)	2 (4.26)	0.380

The distribution of dichotomous categorical variables is expressed by n (%). Continuous variables are expressed as median (interquartile range). OLS, open liver surgery; LLS, laparoscopic liver surgery; RLS, robotic liver surgery; HCC, hepatocellular carcinoma; iCCA, intrahepatic cholangiocarcinoma; pCCA, perihilar cholangiocarcinoma; CRLM, colorectal cancer liver metastases; ASA score, American Society of Anaesthesiologists score.

Table 2 Comparison of perioperative outcomes between OLS, LLS and RLS groups within an intention-to-treat analysis

Perioperative outcomes	OLS (n=124)	LLS (n=101)	RLS (n=47)	P value
Intraoperative outcomes				
Operative time (min)	345 (345–345)	329 (329–351)	392 (319–489)	<0.001
Blood loss (mL)	450 (200–800)	200 (50–425)	200 (50–500)	<0.001
Red blood cells transfusion	18 (14.52)	5 (4.95)	6 (12.77)	0.061
Fresh frozen plasma transfusion	7 (5.65)	0	0	0.014
R0 resection	101 (81.45)	98 (97.03)	43 (91.49)	<0.001
Conversion	–	27 (26.73)	8 (17.02)	0.197
Postoperative outcomes				
Morbidity	64 (51.61)	40 (39.60)	22 (46.81)	0.259
Grade of complications (Clavien-Dindo)				
I grade	10 (8.06)	17 (16.83)	5 (10.64)	0.124
II grade	31 (25.00)	18 (17.82)	8 (17.02)	0.324
III–IV grade	23 (18.55)	5 (4.95)	9 (19.15)	0.006
Liver-specific complications				
Liver failure	4 (3.23)	2 (1.98)	0	0.433
Ascites	14 (11.29)	2 (1.98)	0	0.002
Collection	15 (12.10)	9 (8.91)	8 (17.02)	0.359
Bile leak	11 (8.87)	5 (4.95)	1 (2.13)	0.213
General complications				
Haemorrhage	20 (16.13)	9 (8.91)	4 (8.51)	0.182
Ileus	5 (4.03)	0	2 (4.26)	0.120
Chest infection	6 (4.84)	3 (2.97)	1 (2.13)	0.628
Cardiovascular	4 (3.23)	2 (1.98)	4 (8.51)	0.137
Urinary	0	0	1 (2.13)	0.091
GI bleeding	1 (0.81)	2 (1.98)	0	0.514
Other	10 (8.06)	15 (14.85)	6 (12.77)	0.268
Infectious complications	27 (21.77)	12 (11.88)	6 (12.77)	0.105
Death	1 (0.81)	1 (0.99)	0 (0.00)	<0.001
Reoperation	5 (4.03)	4 (3.96)	3 (6.38)	0.770
Total stay (days)	12 (6–17)	6 (4–11)	5 (3–9)	<0.001
Radiological imaging	28 (22.58)	22 (21.78)	22 (46.81)	0.612
Antibiotic therapy	28 (22.58)	22 (21.78)	13 (27.66)	0.144
Red blood cells transfusion	42 (33.87)	12 (11.88)	6 (12.77)	0.217
Fresh frozen plasma transfusion	18 (14.52)	6 (5.94)	5 (10.64)	0.118
Radio-guided or endoscopic procedures	7 (5.65)	5 (4.95)	4 (8.51)	0.686

The distribution of dichotomous categorical variables is expressed by n (%). For continuous variables, values are expressed as median (interquartile range). OLS, open liver surgery; LLS, laparoscopic liver surgery; RLS, robotic liver surgery; GI, gastrointestinal.

Table 3 Comparison of intra-, postoperative, and total costs between OLS, LLS and RLS groups within an intention-to-treat analysis

Cost drivers	OLS (n=124) (€)		LLS (n=101) (€)		RLS (n=47) (€)		Absolute difference (€)		Difference (%)		P value
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	RLS vs. OLS	RLS vs. LLS	RLS vs. OLS	RLS vs. LLS	
Intraoperative costs											
Medical staff	1,189	348	1,172	326	1,148	378	-41	-24	-3.45	-1.99	0.799
Surgical devices	443	4	602	134	3,864	229	3,421	3,262	772.84	541.80	<0.001
Intraoperative transfusions	128	374	30	135	44	116	-84	14	-65.58	45.63	0.029
Sterilization*	198	-	198	-	198	-	-	-	0.00	0.00	-
Anaesthesia*	117	-	117	-	117	-	-	-	0.00	0.00	-
Histopathological exam*	75	-	75	-	75	-	-	-	0.00	0.00	-
Total	2,150	663	2,194	422	5,446	538	3,296	3,252	153.34	148.23	<0.001
Postoperative costs											
Hospital stays	11,100	7,504	7,027	5,329	4,495	2,572	-6,606	-2,532	-59.51	-36.04	<0.001
Intensive care unit stays	108	415	33	235	250	605	142	217	131.48	657.58	0.026
Antibiotic therapies	50	132	104	322	133	259	83	29	62.41	21.80	0.049
Postoperative transfusions	416	1,014	96	349	180	555	-236	84	-131.11	46.67	0.005
Imaging & procedures	136	735	89	310	133	236	-2	45	-1.60	50.50	0.583
Total	11,810	8,487	7,349	5,921	5,191	3,262	-6,619	-2,158	-56.05	-29.36	<0.001
Total cost	13,960	8,765	9,543	6,125	10,637	3,409	-3,323	1,094	-23.80	11.47	<0.001

* , costs were identified by an extensive reviewed of the scientific literature. OLS, open liver surgery; LLS, laparoscopic liver surgery; RLS, robotic liver surgery.

surgical devices were significantly higher than the other two groups hence leading to globally higher intraoperative costs (+772.8% vs. OLS and +541.8% vs. LLS, $P<0.001$). In the context of intraoperative costs, it is important to note that histopathology exam, anaesthesia and sterilization costs remained consistent, regardless of the approach employed. The authors chose to include these costs in the analysis because they contribute to a more accurate estimate of the total intraoperative procedure costs, even though they do not have any impact in terms of differential analysis. On the other hand, a reduction in postoperative costs was seen for RLS (-56.0% vs. OLS and -29.4% vs. LLS, $P<0.001$) especially sustained by a marked reduction in hospital stays.

Despite the comprehensive analysis, RLS had significantly higher costs for ICU stays compared to both OLS and LLS groups (+131.48% vs. OLS and +657.58% vs. LLS, $P=0.026$). Equally, the costs associated with antibiotic therapies were higher for RLS when compared with their counterparts (+62.4% vs. OLS and +21.8% vs. LLS,

$P=0.049$). However, costs associated with postoperative blood products transfusions were lower for the RLS group if compared with the OLS group and higher if compared with the LLS group (-131.1% vs. OLS and +46.7% vs. LLS, $P=0.005$).

As a results, the balance between intra- and postoperative expenses turned into an overall cost of €13,960 for the OLS group, €9,543 for the LLS group and €10,637 for the RLS group ($P<0.001$).

The analysis of cost distribution (*Figure 1*) reveals that in the OLS and LLS groups, a substantial portion of resources is absorbed by postoperative hospitalization costs (79.5% of total costs for the OLS group and 73.6% of total costs for the LLS group). In contrast, for the RLS group, the predominant resource absorption occurs during intraoperative costs (51.2% of total costs), although this is counterbalanced by a notable reduction in hospitalization-associated costs (42.3% of total costs).

The additional cost of conversion was +37.13% for the

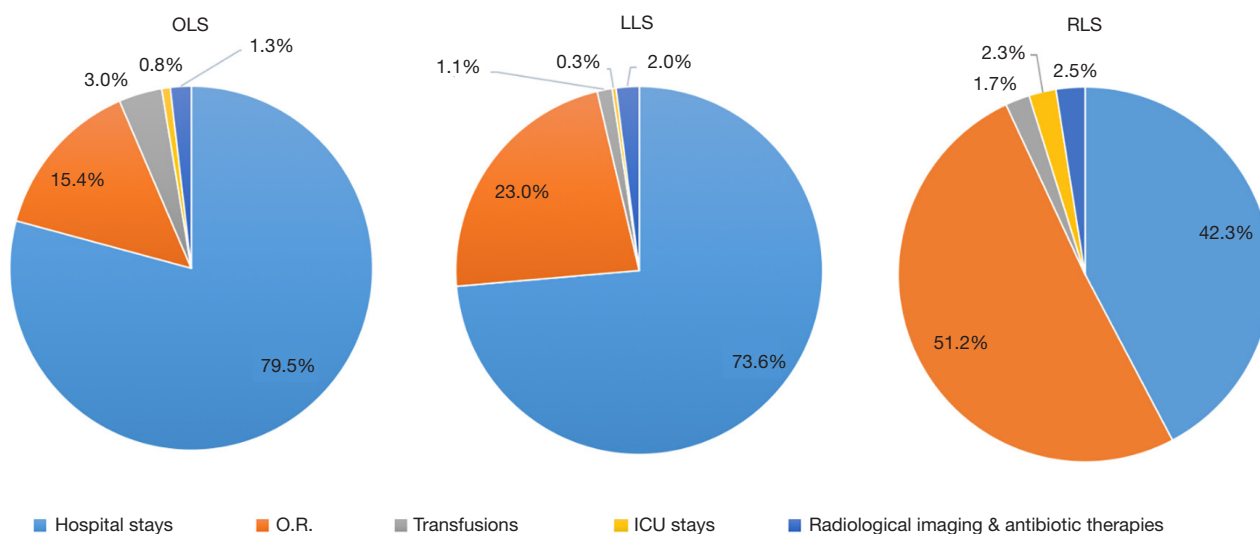


Figure 1 Costs distribution between OLS, LLS and RLS groups. OLS, open liver surgery; LLS, laparoscopic liver surgery; RLS, robotic liver surgery; O.R., operative room; ICU, intensive care unit.

LLS group and +28.52% for the RLS group. However, this difference between the two minimally invasive groups did not reach statistical significance.

In addition, a detailed sub-analysis was conducted to compare the intra-, postoperative and total costs among patients who experience no postoperative complications (Table 4). By narrowing our focus to this specific subgroup, the authors found that the total costs associated with robotic surgery were 82.16% higher than those in the OLS group and 67.58% higher than those in the LLS group. Interestingly, intraoperative costs remained consistent with the main comparative analysis. Notably, the primary factor affecting postoperative costs—specifically the cost of hospital stay—did not exhibit substantial differences among the three groups in this sub-analysis (€3,105 for the OLS group, €3,131 for the LLS group, and €3,068 for the RLS group).

Discussion

RLS is gaining importance in the field of hepatobiliary surgery as a minimally invasive technique. To contribute to the literature in this field, the study aims to perform a rigorous economic analysis comparing open, laparoscopic, and robotic approaches using real-world evidence from two high-volume Italian centers and using a TD-ABC model, which provides a patient-specific cost estimation by considering various contributors to hospital costs.

The economic analysis reveals that RLS has higher intraoperative expenses compared to laparoscopic and open approaches due to the surgical equipment costs. However, the RLS higher intraoperative costs are partially counterbalanced by postoperative savings sustained by a reduction of the hospital stay. A comprehensive breakdown of various cost components is provided, including personnel costs, disposable and reusable device costs, blood transfusion costs, antibiotic therapy costs, and postoperative investigation costs. Addressing the secondary endpoints, the results of the study show that RLS has a longer operative time compared to laparoscopic and open approaches, but the conversion rate is reduced in the RLS group, even though, it does not achieve statistical significance yet. RLS and laparoscopic approaches result in lower intraoperative blood loss compared to open surgery. The RLS and LLS groups also have a higher rate of R0 resections. Postoperative morbidity rates are similar among the three groups, but severe morbidity is significantly higher in the OLS group.

Despite the manageability and intuitiveness of the robotic platform, RLS accounts for less than 8% of all minimally invasive hepatectomies among the European countries (3). One of the most limiting factors is the uncertainty regarding the financial expenditure associated with robotic surgery corroborating that costs are an essential driving factor in health care.

Several studies have evaluated the cost effectiveness

Table 4 Comparison of intra-, postoperative, and total costs between not-complicated OLS, LLS and RLS groups within an intention-to-treat analysis

Cost drivers	OLS (n=16) (€)		LLS (n=34) (€)		RLS (n=33) (€)		Absolute difference (€)		Difference (%)	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	RLS vs. OLS	RLS vs. LLS	RLS vs. OLS	RLS vs. LLS
Intraoperative costs										
Medical staff	759	241	1,020	322	1,099	391	340	79	44.75	7.69
Surgical devices	443	0	581	165	3,861	242	3,418	3,280	771.14	564.38
Intraoperative transfusions	–	–	11	66	31	99	31	20	NA	171.31
Sterilization*	198	–	198	–	198	–	–	–	0.00	0.00
Anaesthesia*	117	–	117	–	117	–	–	–	0.00	0.00
Histopathological exam*	75	–	75	–	75	–	–	–	0.00	0.00
Total	1,592	241	2,002	324	5,381	563	3,789	3,379	237.90	168.64
Postoperative costs										
Hospital stays	3,105	1,293	3,131	1,199	3,068	1,160	–37	–63	–1.19	–2.01
Intensive care unit stays	–	–	99	401	204	557	204	105	NA	106.06
Antibiotic therapies	–	–	41	111	87	181	87	46	NA	112.05
Postoperative transfusions	179	389	30	126	81	337	–98	51	–54.75	171.60
Imaging & procedures	16	52	14	49	91	238	75	77	479.72	552.47
Total	3,300	1,463	3,315	1,428	3,531	1,734	231	216	7.00	6.52
Total cost	4,892	1,647	5,317	1,436	8,912	1,848	4,020	3,595	82.16	67.58

*, costs were identified by an extensive reviewed of the scientific literature. OLS, open liver surgery; LLS, laparoscopic liver surgery; RLS, robotic liver surgery; NA, not applicable.

of robotic surgery in several fields (41-47). In urological surgery, when radical prostatectomy is concerned, the robotic approach seems to have higher costs that are not compensated by the reduced hospital stay. On the contrary, other procedures, such as cystectomy and partial nephrectomy, seem to be more cost-effective (42). In general surgery, some authors have been shown to lower overall cost by reducing complications, improving operative times, and cutting down on supplies (43-47). In more complex cases, such as hepatectomies, the reduction of complications, hospital stay, and readmissions could translate into a real cost benefit, even if the initial acquisition and intraoperative costs are higher. The largest monocentric series published by Sham *et al.* compared the costs of robotic hepatectomies (n=71) with open hepatectomies (n=88) conducted between 2011 and 2015. Although the robotic surgery group had

higher peri-operative costs, the post-operative and total costs were lower than those of the control group underwent open hepatectomies (19). Similarly, in a retrospective study, Daskalaki *et al.* reported a significant overall lower rate of complications and costs in the robotic group than the subset of patients who underwent open liver resections (20). Aziz *et al.* utilized a nationwide database to assess long-term readmission rates for liver resections confirming that using robotics provides a financial benefit over open and LLS for patients underwent open and LLS (16). On the contrary Xu *et al.*, investigating a single center series of patients that underwent liver resection for hilar cholangiocarcinoma, founded a hospital expenditure much higher in the robotic group compared to the traditional open surgery (21). Scientific evidence has been recently enriched by a meta-analysis published by Gavriilidis *et al.* Analysing 1,064

papers, the authors selected 79 articles with a population of 25,210 patients. The study results showed a cost saving of \$1,197 by adopting the open technique and \$759 by adopting the laparoscopic technique when compared to the robotic approach. Similarly, the laparoscopic approach showed a higher cost, approximately \$426 more than the open approach (7). However, the procedure related costs did not statistically differ among the three groups. Previous studies have yielded conflicting results on the cost-effectiveness profile of RLS due to variations in cost calculation methods and the lack of consideration for the initial purchase costs of the robotic platform. The findings of the present study are a step forward with respect to the existent literature. Through a TD-ABC model, the cost of personnel and supply resources consumed by each patient and the time spent performing each activity have been extracted and validated by an expert opinion to perform a rigorous economic analysis that lay the foundation for future methodology, where reproducibility have to be an essential goal to evaluate cost trends.

Similarly to pure laparoscopy, RLS offers several clinical advantages over open surgery, including lower blood loss, decreased morbidity, shorter hospitalization, and faster recovery. RLS has shown efficacy in treating malignant diseases in terms of oncological adequacy while preserving the minimally invasive nature of the procedure. One of the major drawbacks of laparoscopic surgery is reduced dexterity and difficulty in performing complex tasks. Although laparoscopy is feasible, the caudal view and the linear shape of the instruments make surgeons more concerned about possible injuries in critical areas and any bleeding more challenging to control especially in proximity of major vessels or in case of vascular resections. Robotic technology addresses these limitations by providing instruments with high degrees of freedom, a stable 3D vision, tremor suppression algorithms, and enhanced ergonomics for the surgeon. This allows for more precise and complex manoeuvres, making RLS suitable for difficult liver resections such as postero-superior segments, major hepatectomies, and time-consuming interventions requiring extensive dissections or reconstructions. In a multicenter study by Cipriani *et al.*, the authors concluded that robotics can favour the operative feasibility of difficult resections, possibly extending the indications for minimally invasive approaches for liver resections (2). Indeed, the use of robotic instrumentation may significantly resize complexity contributing to the large-scale diffusion of procedures with a high risk of injuries, such as performing an oncologically

adequate lymph nodal dissection (48).

In a previous study by our group the outcomes of open *vs.* laparoscopic *vs.* robotic LND were specifically compared demonstrating a better performance of the robotic approach over laparoscopic approach (and both approaches over the open technique). The advantages of the robotic approach included image magnification, panoramic view, and the combination of specialized instrument, such as the Maryland bipolar forceps with empowered precision cutting and haemostatic ability and the prograsp forceps with a strong grip and wrist capabilities. These features allowed for effective exposure of the surgical field without obstructing the visual and operative field of the surgeon and provided a gentle dissection without incurring the risk of damage or breakage. Consequently, the use of robotics significantly reduced the time required for LND when compared to the laparoscopic approach (49).

Analysing the secondary endpoints, according with previous studies, the RLS group had a significantly longer operative time comparing with the other two groups, suggesting that robot docking and set-up still impact on the global length of the procedures (50). In addition, the fact that the two minimally invasive groups resulted in lower intraoperative blood loss supports the possibility of transection and haemostasis as accurate for RLS as for LLS even although an ultrasonic dissector specifically designed for robotics is not available yet. Although the production of a robotic ultrasonic dissector remains desirable this current absence is probably counterbalanced by the existing advanced robotic instruments that enable an accurate parenchymal dissection while preserving the vascular structures. Thereby, in our series, robotics show adequacy in the treatment of malignant diseases, and can offer advantages in achieving oncological radicality even presenting higher median size for the largest lesion. The data can be explained by the enhanced dexterity of robotics as it enables an accurate tracking of regulated transection planes, which is particularly challenging during laparoscopy (51). According with this result, even though no significant differences were recorded among the two minimally invasive groups in terms of rate of conversion, when analysing the reasons for conversion, RLS was associated with reduced conversions for oncologic radicality. Instead, the lower rate of R0 resections in the OLS group can be attributed to the fact that this group dealt with a higher proportion of technically challenging cases. These cases, characterized by a major tumor burden and the potential infiltration of vascular structures, are frequently addressed using an open

approach due to the complexity of the surgery.

Furthermore, it is important to highlight that in the robotic group, a significantly higher percentage of patients had a history of previous abdominal surgery (78.72% *vs.* 56.44% for LLS *vs.* 50% for OLS, $P=0.003$). Notably, this did not lead to an increased conversion rate due to adhesions. This outcome underscores the efficacy of robotic instruments, likely facilitating effective adhesiolysis even in the most challenging cases.

Finally, there is a growing awareness of the fact, that the robotic learning curve in liver surgery is faster than the laparoscopic one. A steeper learning curve in comparison to LLS can be seen as a further advantage of the robotically assisted technique. Passing the learning curve helps to achieve a better cost-effectiveness, as operation time is decreasing and surgical outcomes are improving (52).

Intraoperative advantages directly translate into a favourable postoperative course. RLS in fact was associated with lower high-grade morbidity (grade 3–4 Clavien-Dindo), in particular ascites, and shorter postoperative hospital stay, significantly reducing costs needed for the postoperative management comparing with the other two groups. Thus, it is crucial to emphasize that among the statistically significant findings of our analysis, we have observed notable post-operative outcomes and, correspondingly, a reduction in post-operative costs related to RLS group. This observation potentially reinforces the robustness of the conducted cost analysis.

Nevertheless, it is essential to highlight that in the robotic group, cardiovascular accidents constituted 33.3% of severe complications. While the limited sample size prevents definitive conclusions, this data could be interpreted as a potential consequence of extended operative times, exposing patients to prolonged pneumoperitoneum (Table 5).

In the economic sub-analysis of patients without postoperative complications, total costs for robotic surgery were notably higher than those for open and laparoscopic approaches. This increase was primarily due to the variations in hospital stay expenses, which, in this case, were relatively similar among the three groups. This economic finding aligns with the clinical observation that the median LOS was 4.5 days for the OLS group, 4 days for the LLS group, and 4 days for the RLS group. Consequently, the initial hypothesis is further supported, indicating that the robotic approach is particularly advantageous for high-risk hepatectomies prone to postoperative complications, such as complex liver resections.

Regarding the ICU stay, it is worth to mention that the results in terms of absorption of direct healthcare costs for the robotic approach could be overestimated since authors considering a cautious management of the initial cohort. On the other hand, in order to give an explanation on the higher usage and costs of antibiotic treatment in the RLS group, it is relevant to reference that in this group, patients who underwent hilar LND are more prominently represented, and these cases more frequently necessitate post-operative antibiotic treatment.

Concerning patient selection, the RLS group presented a higher proportion of cases with benign diseases. It is important to clarify that a significant subset of these patients was affected by benign diseases of the intrahepatic biliary tract (i.e., inflammatory stenosis and hepatolithiasis). These conditions frequently required complex parenchymal dissection due to the distortion of intrahepatic ducts and the vascular changes resulting from the inflammatory extension of cholangitis (53). Given this challenging anatomical situation, the decision to opt for a robotic approach is related to enhanced dexterity and precise cutting capabilities, crucial for effective manoeuvres within an inflammation affected environment. The ability to perform delicate microsuturing with robotic assistance further supports the suitability of robotic approach in such cases.

In order to provide a real-life picture of allocation to each available approach, a simple comparison without propensity score analysis was chosen as the best design to fulfil study endpoints. Provided the specific indications and contraindications for each approach—including the complexity of the disease, the presence of severe comorbidities, anatomical constraints and the need for extensive liver resections—a matching according to preoperative variables would not have been appropriate and not informative as there were substantial differences between patients who underwent minimally invasive procedures and those who received open surgery. Hence the absence of a propensity score analysis in this scenario reflects the inherent complexity and variability of patient cases, where individualized treatment plans are essential to ensure the best possible outcomes.

However, the study is not exempt from limitations. The sample size was still relatively limited, which could affect the statistical power of the results. With a small sample, the study may not capture the full range of variations and potential outcomes, reducing the reliability of the findings. The second limitation relates to the economic analysis conducted in the study. The costs were derived

Table 5 Comparative sub-analysis of severe complications between the OLS and the RLS groups

Severe complications (Clavien-Dindo 3–5)	OLS (n=23)	RLS (n=9)	P value
3a	11 (47.8)	6 (66.7)	0.337
Bile leak	5 (21.7)	1 (11.1)	
Ascites	1 (4.3)	0 (0.0)	
Collection	4 (17.4)	2 (22.2)	
Bowel obstruction	1 (4.3)	0 (0.0)	
Cardiovascular disease	0 (0.0)	3 (33.3)	
3b	8 (34.8)	3 (33.3)	0.938
Haemorrhage	2 (8.7)	1 (11.1)	
Bowel obstruction	2 (8.7)	2 (22.2)	
Pneumothorax	1 (4.3)	0 (0.0)	
Choleperitoneum	3 (13.0)	0 (0.0)	
4a	2 (8.7)	0 (0.0)	0.361
Liver failure	1 (4.3)	0 (0.0)	
Respiratory failure	1 (4.3)	0 (0.0)	
4b	1 (4.3)	0 (0.0)	0.525
Multiorgan failure	1 (4.3)	0 (0.0)	
5	1 (4.3)	0 (0.0)	0.525
Death	1 (4.3)	0 (0.0)	

The distribution of dichotomous categorical variables is expressed by n (%). OLS, open liver surgery; RLS, robotic liver surgery.

from literature sources, including the acquisition costs of the robotic platform and the costs of dissectors based on average prices obtained from regional Italian tenders. Relying solely on literature sources may introduce potential inaccuracies and regional variations in the cost estimates. However, to enhance the generalizability of the results, the study utilized existing literature sources instead of data from administrative databases. In fact, these sources provided a broader perspective and allowed for the consideration of various settings beyond the specific centers involved in the study. Another relevant limitation of the study is the failure to consider the long-term amortization of the robotic platform cost, which could have a significant impact on the cost-effectiveness profile considering a longer time horizon. This aspect was not addressed because reimbursement diagnosis-related groups (DRGs) vary across regions, and it would have been necessary to take into account also all procedures performed using the robotic platform by all the other surgical units. By not accounting for the long-term cost implications and considering the broader

range of procedures conducted with the robotic platform, the study may underestimate or overlook the true cost-effectiveness value of the robotic approach. Future research endeavors should delve into assessing long-term patient outcomes, refining cost-saving measures, and exploring the implications of new robotic systems to enhance the overall effectiveness and applicability of RLS in clinical practice.

Conclusions

This study emphasizes the potential advantages of RLS in complex resections and underscores the need for a thorough economic analysis for cost-effectiveness, providing real-world evidence and detailed economic insights using a TD-ABC model. Despite RLS incurring higher total intraoperative costs, including ICU stays and surgical devices, when compared to OLS and LLS groups, it demonstrated lower total postoperative costs, resulting in an overall cost of €10,637, compared to €13,960 for OLS. Anticipated reductions in acquisition costs with the

introduction of new robotic systems and increased market competition make robotic surgery a favoured minimally invasive technique. As adoption expands, proficiency among surgeons and healthcare providers is expected to lead to streamlined procedures, shorter operative times, and improved patient outcomes, contributing to lowered overall costs associated with RLS. Over time, standardization and proficiency in using robotic systems have the potential to optimize workflow, reduce complications, and yield cost savings. However, it is essential to consider factors such as maintenance, upgrades, and ongoing training when evaluating the overall cost-effectiveness of robotic technology. A comprehensive long-term cost analysis should encompass these elements to grasp the economic implications of widespread adoption in minimally invasive techniques.

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Footnote

Data Sharing Statement: Available at <https://hbsn.amegroups.com/article/view/10.21037/hbsn-23-407/dss>

Peer Review File: Available at <https://hbsn.amegroups.com/article/view/10.21037/hbsn-23-407/prf>

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at <https://hbsn.amegroups.com/article/view/10.21037/hbsn-23-407/coif>). L.A. serves as an unpaid editorial board member of *Hepatobiliary Surgery and Nutrition*. The other authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. This study adheres to the principles outlined in the Declaration of Helsinki (as revised in 2013). The study population derived from the Italian “I GoMILS” registry. Ethical approval for the registry was granted by the Ethics Committee of the promoting center and shared among the participants (IGOMILS-OSR of March 6, 2014—available at: <https://www.cr-technology.com/igomils/eclinical/website/documents.aspx>). Written consent from subjects was waived.

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