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Systematic Review

Clinical outcomes and cost of robotic ventral hernia repair: systematic review

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Abstract

Background: Robotic ventral hernia repair (VHR) has seen rapid adoption, but with limited data assessing clinical outcome or cost. This systematic review compared robotic VHR with laparoscopic and open approaches.

Methods: This systematic review was undertaken in accordance with PRISMA guidelines. PubMed, MEDLINE, Embase, and Cochrane databases were searched for articles with terms relating to 'robot-assisted', 'cost effectiveness', and 'ventral hernia' or 'incisional hernia' from 1 January 2010 to 10 November 2020. Intraoperative and postoperative outcomes, pain, recurrence, and cost data were extracted for narrative analysis.

Results: Of 25 studies that met the inclusion criteria, three were RCTs and 22 observational studies. Robotic VHR was associated with a longer duration of operation than open and laparoscopic repairs, but with fewer transfusions, shorter hospital stay, and lower complication rates than open repair. Robotic VHR was more expensive than laparoscopic repair, but not significantly different from open surgery in terms of cost. There were no significant differences in rates of intraoperative complication, conversion to open surgery, surgical-site infection, readmission, mortality, pain, or recurrence between the three approaches.

Conclusion: Robotic VHR was associated with a longer duration of operation, fewer transfusions, a shorter hospital stay, and fewer complications compared with open surgery. Robotic VHR had higher costs and a longer operating time than laparoscopic repair. Randomized or matched data with standardized reporting, long-term outcomes, and cost-effectiveness analyses are still required to weigh the clinical benefits against the cost of robotic VHR.

Introduction

Adult ventral hernias are common[1], and include epigastric, umbilical, Spigelian, and incisional hernias. Incisional hernias develop after 10–15 per cent of laparotomies[2], and the risk of recurrence increases with each subsequent repair[3]. Over 60 per cent of ventral hernias are repaired using an open approach, although there has been a nearly 45-fold increase in repairs using robotics technology over the past decade[4].

Morbidity rates associated with open repair are high owing to patient factors and hernia complexity, with short-term complication rates of up to 40 per cent[5]. Laparoscopic repair has been recommended for large epigastric or umbilical hernias by the European and Americas Hernia Societies[6], largely on the basis of decreased wound morbidity. Robotic surgery augments the laparoscopic approach with its magnified three-dimensional visualization of the operative field, stable platform, and superior range of motion[7] that may be particularly beneficial for complex hernias.

The cost of robotic surgery for ventral hernia repair (VHR) is also unknown. Acquisition and implementation require substantial investment along with expenses for annual maintenance contracts, instrument purchases, staff and training, and infrastructure upgrades[8]. It is imperative to weigh the costs of robotic surgery relative to clinical efficacy.

A systematic review[9] in 2019 reported on limited short-term outcomes following VHR but without cost outcomes. New studies, including two RCTs, have since been published. The present systematic review analysed intraoperative and postoperative

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clinical outcomes and costs of robotic VHR compared with laparoscopic and open approaches.

Methods

This review formed part of a larger report commissioned by the Department of Veterans Affairs on clinical and cost outcomes of robotic procedures for cholecystectomy, inguinal hernia repair, and VHR[10]. PRISMA standards[11] were adhered to, and the *a priori* protocol registered in PROSPERO (CRD42020156945).

Literature search

English-language articles in PubMed, MEDLINE, Embase, and Cochrane (all databases) from 1 January 2010 to 10 November 2020 were searched. Search terms relating to 'robotic surgical procedures' or 'robot-assisted', 'cost effectiveness', and 'ventral hernia' or 'incisional hernia' were used. Studies published before 2010 were not included, as robotic procedures were not widely performed then, and many surgeons and their support staff may have been in the early adoption phase for both the technique and implementation of the robotic platform.

Study selection and data collection

All stages of review were completed by two independent team members, and disagreements were resolved through discussion. RCTs and observational studies comparing robotic VHR with either laparoscopic or open approaches were included. Studies with fewer than 10 patients per arm, and those that evaluated only emergency repairs, used a hybrid approach (open VHR with robotic transversus abdominis release (TAR)), or assessed parastomal hernias were excluded. Studies that used the same national databases with duplicate patients were excluded if there was greater than 1-year overlap, with an exception made for one study[12] that reported a unique outcome. When selecting studies for inclusion using the same databases, peer-reviewed studies with superior methodology (propensity matching) or longer time span were preferentially included. The same inclusion and exclusion criteria were applied to the economic analysis.

Data were collected on study design, sample size, patient and hernia characteristics, intraoperative outcomes, short-term postoperative outcomes, long-term outcomes, and length of follow-up. Patient characteristics included: age, race/ethnicity, sex, BMI, ASA fitness grade, and co-morbidities. Hernia characteristics included: hernia area or length, whether the hernia was primary or recurrent, whether the hernia was midline, and repair technique. Intraoperative outcomes included: operating room (OR) time, estimated blood loss, transfusions, intraoperative complications, conversions to open surgery, use of mesh, rate of fascial closure, method of mesh fixation, and presence of concurrent procedures. Short-term outcomes were defined as those occurring 30 days or less after surgery, including length of hospital stay, surgical-site infection (SSI), readmission rate, reoperation rate, emergency department visits, all complications, and mortality. Studies[13,14] reporting 'postoperative infection' provided an estimated SSI outcome. Long-term outcomes were defined as those occurring after 30 days, and included readmission rate, mesh infection, chronic pain, recurrence, and quality of life. Economic analyses included the source and type of cost data and estimated mean or median costs for each approach. Costs originally calculated in US dollars were converted to euros at an exchange rate of US $1.2 to €1.

Risk of bias and certainty of evidence

The risk of bias in RCTs was assessed with the Cochrane risk-of-bias tool[15]. Each observational study was assessed for risk of bias using the Cochrane Risk Of Bias In Non-Randomized Studies of Interventions (ROBINS-I) tool[16].

Criteria of the Grading of Recommendations, Assessment, Development, and Evaluation (GRADE) working group were used to assess the overall certainty of the evidence[17].

Statistical analysis

The data synthesis is narrative; meta-analysis was not conducted owing to sources of heterogeneity in clinical and cost outcomes of the RCTs and observational studies. RCTs and studies that performed propensity matching were considered more valuable in terms of summarizing the data than non-matched studies that did not account for clinical differences between patient cohorts.

The mean (or median) and a measure of variation (s.d., i.q.r., range, or c.i.) were extracted for continuous outcomes. For binary outcomes, a count and percentage were retrieved. $P < 0.050$ was considered significant. When data were presented only for subgroups, pooled values were back-calculated.

Graphical representations of risk and mean differences with 95 per cent confidence intervals were plotted when available or estimated using counts and sample sizes using R 4.0.2[18]. Annotations were made where significance differed between the study-reported P value and calculated risk or mean differences and 95 per cent confidence intervals. For rare outcome events, risk differences (RDs) were used preferentially during analysis.

Results

Literature search

A total of 3604 citations were identified, 3599 potentially relevant citations from databases and five publications recommended by experts. From these, 397 abstracts were included for screening, and 55 articles for full-text review. Of these, 30 full-text publications were excluded for the following reasons: duplicate data (9), no outcomes of interest (8), incorrect comparison (6), case series (4), review or editorial (2), and full text not available (1). In total, 25 studies met the inclusion criteria: three RCTs[19–21] and 22[12–14,22–40] observational studies, of which two[37,39] were included for cost outcomes only (*Fig. 1*).

Study characteristics

One RCT[19], of 38 patients comparing robotic with laparoscopic VHR, was published as a conference abstract from a single institution in Brazil. Details of the operative techniques were not provided, and data supporting intraoperative outcomes and the majority of postoperative outcomes were not reported. This study was judged to have a high risk of bias and was omitted from the final synthesis (*Table 1*).

The remaining two RCTs compared robotic with laparoscopic intraperitoneal onlay mesh (IPOM) repair (*Table 2*). One[20] was multi-institutional and included 123 patients, and the other[21] included 75 patients at a single institution.

Twenty-two studies were observational, of which four[22,34,36,37] were conference abstracts, and two[37,39] provided cost outcomes only. Eleven studies[12–14,23–25,27,29,30,36,39] used data from prospectively maintained databases, nine[12,13,24,25,27,32,34–36] compared robotic VHR with open repair (*Table 3*), and 15[13,14,22,23,26,28–31,33,36–40] compared robotic surgery with laparoscopy. All observational studies were performed in the USA, except for two studies[27,35] from

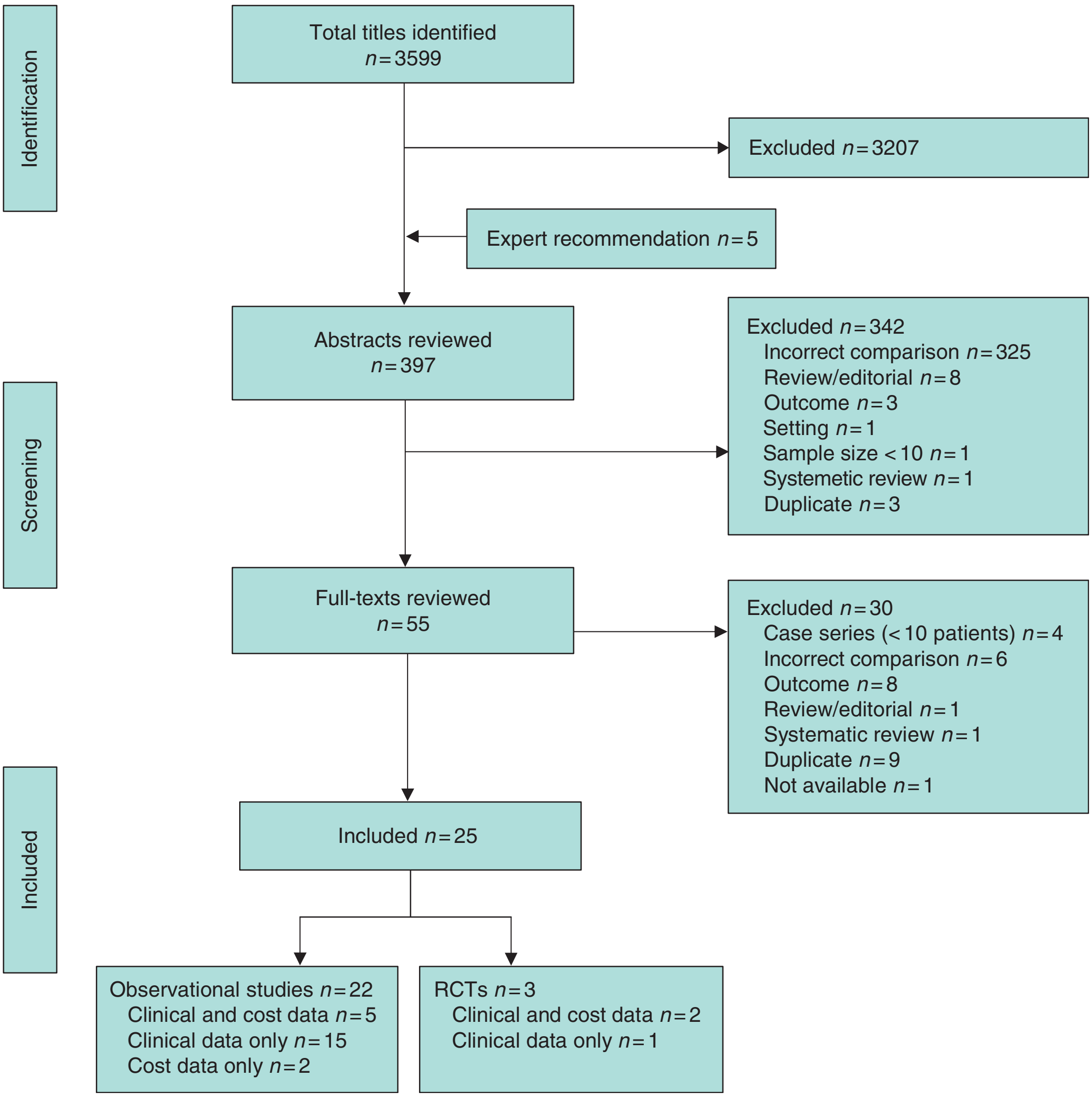

Fig. 1 PRISMA flow diagram showing selection of articles for review

Table 1 Risk-of-bias assessment for RCTs using Cochrane risk-of-bias tool

Reference, year	Random sequence generation	Allocation concealment	Blinding of participants and personnel	Blinding of outcome assessment	Incomplete outcome data	Selective reporting	Other sources of bias
Abdalla *et al.*[19] 2017*	○	●	●	● QoL	○	●	
Olavarria *et al.*[20] 2020	○	○	● Surgeon not blinded; patient and rest of research team blinded	○	○	○	● Study supported by investigator-initiated grant from Intuitive
Petro *et al.*[21] 2021	○	○	● Single-blinded	● Not stated whether outcome assessor was blinded; patient-recorded outcomes concealed	○	○	● Study funded by grant from Intuitive; 6 authors (including 1st author) received grants from Intuitive

*Conference abstract. ○, Low risk of bias; ● high risk of bias; QoL, quality of life.

Table 2 Study, hernia, and patient characteristics in studies comparing robotic *versus* laparoscopic surgery

Study characteristics			Hernia characteristics		Patient data			
Reference, year, country	Sample size		Hernia area (cm²)*		Age (years)*		BMI (kg/m²)*	
	Robotic	Laparoscopic	Robotic	Laparoscopic	Robotic	Laparoscopic	Robotic	Laparoscopic
RCTs								
Olavarria *et al.*[20] 2020, USA	65	58	3.0 (2.0–5.0)††§	3.0 (1.0–4.5)††§	50.1(13.3)	48.0(12.9)**	32.4(4.6)	31.8(5.4)**
Petro *et al.*[21] 2021, USA	39	36	5 (3–8)††§	5 (2–8)††§	56 (50–70)	55 (49–60)**	35 (31–39)††	31 (27–36)††,††††
Studies with propensity matching								
Altieri *et al.*[23]¶ 2018, USA	679	2089	–	–	> 55: 67.6%	> 55: 47.4%††††	–	–
LaPinska *et al.*[30] 2020, USA	615	615	4(2)§	4(3)§	55(14)	56(14)**	33(7)	33(8)**
Song *et al.*[36]# 2017, USA	94	94	–	–	–	–	–	–
Walker *et al.*[38]¶ 2018, USA	142	73	4.3(3.2)§	4.1(2.1)§	53.2(13.2)	49.5(13.3)**	31.6(5.1)	35.7(7.9)††††
Studies without propensity matching								
Alimi *et al.*[22]# 2020, USA	46	100	17.5	119.5	–	–	28.8	31.6**
Armijo *et al.*[13] 2018, USA	465	6829	–	–	59(13.1)	57(13.2)**	–	–
Chen *et al.*[26] 2017, USA	39	33	3.07 (1–9)‡§	2.07 (0.5–5)‡§	47.2 (24–69)‡	46.6 (27–68)‡**	33 (23–53)	32 (25–45)‡**
Coakley *et al.*[14] 2017, USA	351	32 243	–	–	59.4(14.6)	57.4(14.9)††††	–	–
Gonzalez *et al.*[28] 2015, USA	67	67	–	–	56.6(14.5)	55.0(13.2)**	34.7(9.0)	33.5(9.5)**
Khorgami *et al.*[29] 2019, USA	99	3600	–	–	–	–	–	–
Lu *et al.*[31] 2019, USA	86	120	7.1(2.6)§	5.5(1.8)§	50.8(12.8)	53.2(14.6)**	34.4(7.4)	31.3(6.1)††††
Mudyanadzo *et al.*[33] 2020, USA	16	19	–	–	–	–	–	–
Tan *et al.*[37]# 2018, USA	46	47	–	–	55.1	61.6††††	–	–**
Warren *et al.*[39] 2017, USA	53	103	82.5(69.8)	88.0(94.0)	52.9(12.3)	60.2(13.4)††††	34.7(7.4)	35.7(9.5)**
Zayan *et al.*[40] 2019, USA	16	33	–	–	49.0 (42.2–55.2)††	51.5 (46.5–56.2)††**	48.97 (42.15–55.23)††	33.71 (30.84–42.88)††,††††

*Values are mean(s.d.) unless indicated otherwise; values are ††mean (i.q.r.) and ‡mean (range). §Hernia length in centimetres. ¶Unmatched data presented, as matched demographic data not reported. #Conference abstract. **P not significant. ††††P < 0.050. A version of this table featuring additional data is available as *Table S1* online.

Table 3 Study, hernia, and patient characteristics in studies comparing robotic *versus* open surgery

Study characteristics			Hernia characteristics		Patient data			
Reference, year, country	Sample size		Hernia area (cm²)*		Age (years)*		BMI (kg/m²)*	
	Robotic	Open	Robotic	Open	Robotic	Open	Robotic	Open
Studies with propensity matching								
Carbonell *et al.*[25] 2018, USA	111	222	87.96(67.57)	80.13(74.02)	55.59(12.36)	55.08(13.76)#	33.88(7.30)	33.23(7.39)#
Martin-del-Campo *et al.*[32] 2018, USA	38	76	13.5(4.5)§	13.5(4.5)§	58.9(12.7)	58.8(11.8)#	33.1(8.8)	33.51(5.7)#
Song *et al.*[36] 2017, USA	96	96	–	–	–	–	–	–
Studies without propensity matching								
Armijo *et al.*[13] 2018, USA	465	39 505	–	–	59(13.1)	57(13.3)#	–	–
Bittner *et al.*[24] 2018, USA	26	76	235(107)	260(209)	52.4(12.9)	54.6(14)#	33.4(9)	32.1(7)#
Dauser *et al.*[27] 2020, Austria	16	10	–	–	71	62#	28.4 (22.0–40.5)†	25.7 (23.6–29.8)†#
Guzman-Pruneda *et al.*[12] 2020, USA	42	194	61 (40–120)‡	193 (106–300)‡	59 (54–65)‡	62 (53–68)‡#	32 (28–39)‡	31 (28–35)‡#
Nguyen *et al.*[34], 2019, USA	27	16	216	242	55.4(12.4)	58.6(10.4)#	32.2(6.4)	33.3(5.5)#
Reeves *et al.*[35] 2020, Australia	13	13	–	–	69.9(13.3)	64.8(14.7)#	–	–

#*Values are mean(s.d.) unless indicated otherwise; values are †median (range) and ‡median (i.q.r.). §Hernia length in centimetres. ¶Conference abstract. P not significant. A version of this table featuring additional data is available as *Table S2* online.

Austria and Australia. Ten studies[12–14,23,25,29,30,32,35,38] were multi-institutional, 11[22,24,26–28,31,33,34,37,39,40] were from a single institution, and one study[36] did not specify the number of centres. Propensity matching was performed in six studies[23,25,30,32,36,38]. The sample size varied from 26 to 46 799 patients.

Hernia characteristics, such as size, whether the hernia was recurrent or midline, repair technique, fascial closure, and mesh fixation technique, were reported inconsistently. Where reported, about three-quarters of ventral hernias were primary. The most common repair technique in studies comparing robotic and open approaches was retrorectus VHR with or without TAR, whereas IPOM repair was more common in studies comparing robotic and laparoscopic approaches. With regard to mesh fixation, tacks were used more frequently in laparoscopic VHRs, whereas sutures and adhesives were used primarily in robotic and open repairs.

The two RCTs included in the final analysis were deemed to have a moderate risk of bias (*Table 1*). Both suffered from lack of blinding of the surgeon given the nature of the trial design, and both were funded by the manufacturer of the robotic platform (Intuitive Surgical, Sunnyvale, CA, USA).

The majority of observational studies had a high risk of confounding bias, as baseline characteristics differed between approaches. Selection bias, bias in the measurement classification of interventions, bias owing to deviation from intended interventions, and bias in selection of the reported result were generally low. Studies reporting only short-term outcomes were presumed to have minimal loss to follow-up and therefore to be at low risk of bias because of missing data. Studies with long-term outcomes were classified as being at higher risk of bias owing to missing data if follow-up rates were low (less than 70 per cent) or not reported. For bias in measurement of outcomes, self-reported outcomes relating to pain and quality of life had a moderate risk of bias because of the subjectivity of these measurements. Objective assessments, such as length of hospital stay, complications, OR time, recurrence, and pain as assessed by narcotic use, had a low risk of bias. Only six studies were propensity-matched, but there was inconsistency concerning the matched variables (such as patient characteristics or hernia size) (*Table 4*). The non-matched studies had a high risk of bias, whereas the matched studies were deemed to have a moderate risk of bias. Seven[24,25,30–32,38,39] studies disclosed author involvement with Intuitive Surgical to varying extents.

Intraoperative outcomes

Robotic VHR took longer than both open and laparoscopic surgery in most studies (*Tables 5* and *6*). Seven[12,24,25,32,34–36] of eight studies, including all three with propensity matching, demonstrated increased operating time with robotic compared with open surgery by 66–88 min, whereas there was no statistically significant difference in the remaining non-matched study[27]. For the robotic *versus* laparoscopic comparison, all nine studies[20,21,26,28,30,31,36,38,40] reporting duration of surgery, including two RCTs and two propensity-matched studies, reported a longer operating time with robotic VHR by a median of 54 min.

The rate of intraoperative complications was 0–5 per cent among the five studies that compared this outcome between robotic and open surgery, of which four[12,25,32,36], including three with propensity matching, did not show a statistically significant difference (*Table 5*). One non-matched study[24] found a decreased intraoperative complication rate with robotic surgery when the RD was calculated. Intraoperative complication rates for robotic and laparoscopic VHR ranged between 1 and 6 per cent among the three studies[21,30,36] reporting this outcome and were no different between the approaches (*Table 6*).

Three propensity-matched studies assessed transfusion outcomes between the three approaches. Transfusion events were rare, with a rate ranging between 0 and 7 per cent among all studies. Both studies[32,36] assessing transfusion in robotic and open VHR found a reduced transfusion rate with robotic surgery (0 *versus* 6.6 per cent; RD −0.066, 95 per cent c.i. −0.121 to −0.010; 0 *versus* 5.2 per cent, $P = 0.02$). Comparing robotic with laparoscopic VHR, one study[36] demonstrated fewer transfusions during robotic surgery (0 *versus* 5.3 per cent; $P = 0.02$), whereas the other[30] found no significant difference between the two approaches (0.2 *versus* 0 per cent; $P = 1.000$).

Four studies reported the rate of conversion to open from minimally invasive approaches, which ranged from 0 to 4 per cent. Two propensity-matched studies[30,36] reported fewer conversions to open operation with robotic surgery compared with laparoscopy (0.5 *versus* 2.3 per cent, $P = 0.007$; 2.1 *versus* 13.9 per cent, $P = 0.003$); however, the RCT[20] and one non-matched study[28] did not find a difference in conversion rates between the approaches (1.5 *versus* 1.7 per cent, $P = 0.84$; 1.5 *versus* 4.5 per cent, $P = 0.310$).

Short-term postoperative outcomes

Comparing robotic with open VHR, all nine studies[12,13,24,25,27,32,34–36], including three that were propensity-matched, demonstrated a shorter hospital stay in the robotic cohort, with one study[27] reporting an absolute reduction of 8 days (*Fig. 2* and *Table 7*). There were smaller differences between robotic and laparoscopic VHR; four[23,30,33,40] of 14 studies, including two with propensity matching, reported a decreased duration of hospital stay after robotic surgery, with a mean absolute difference of 1 day (*Table 8*). Nine[13,14,20,21,26,28,29,31,36] of the remaining 10 studies, which included both RCTs and one propensity-matched study, did not find any difference in length of stay between robotic and laparoscopic VHR.

With regard to SSI rates, two[13,32] of eight studies, which included one propensity-matched study, found a decreased incidence associated with robotic repair compared with the open approach when RDs were calculated (*Table 7*). The remaining six[12,24,25,27,34,36] showed no statistically significant difference. In the robotic and laparoscopic comparison, one non-matched study[38] demonstrated a lower SSI rate in the robotic cohort, whereas another[13] found a higher SSI rate in the robotic group (*Table 8*). The remaining six studies[14,20,26,28,30,36], which included one RCT and two propensity-matched studies, did not report a difference in SSI rates between robotic and laparoscopic hernia repair.

Of the seven studies that assessed readmission rate after robotic and open VHR, one non-matched study[13] found decreased rates following robotic repair, and the remaining six[12,24,25,27,32,34], including two matched studies, found no difference. None of the six studies[13,20,21,23,30,31] evaluating readmission rates showed a difference between robotic and laparoscopic VHR.

Total complication rates were reported in eight studies comparing robotic with open VHR (*Table 7*). Five studies[13,25,27,32,36], including three with matching, noted a lower postoperative morbidity rate after robotic surgery, whereas the remaining three[12,24,35] non-matched studies found no difference. Of note, one non-matched study[27] pooled both intraoperative and postoperative complications. Of the 10 studies evaluating complication rates in robotic and laparoscopic VHR, two[23,31] demonstrated decreased morbidity rates following robotic surgery, included one matched study (*Table 8*). One non-matched study[13] reported an increased morbidity rate after robotic VHR. The remaining seven studies[14,20,21,26,28,30,36], including two RCTs and two matched studies, found that total complication rates did not stays differ between the robotic and laparoscopic approaches.

Short-term mortality was rare among all approaches, with rates of between 0 and 1 per cent. Mortality rates did not differ in any of the four studies[13,24,25,32] comparing robotic and open hernia repair, or the four[13,14,28,30] comparing robotic and laparoscopic VHR.

Pain

Three studies evaluated short-term pain outcomes in robotic and open VHR. One matched study[36] found decreased narcotic use measured as milligram morphine equivalents and a trend toward decreased patient-controlled analgesia use following robotic repair. Neither of the two remaining studies[13,25], one matched and one not matched, demonstrated a difference in pain between the robotic and open approaches assessed in terms of readmission owing to pain and narcotic requirements.

Five studies evaluated short-term pain outcomes in robotic and laparoscopic VHR. One of the RCTs[21] demonstrated a greater improvement in pain from baseline following laparoscopic surgery, as assessed by the Patient-Reported Outcomes Measurement

Table 4 Risk of bias in observational studies determined using ROBINS-I tool

Reference	Confounding	Selection bias	Bias in measurement classification of interventions	Bias due to deviations from intended interventions	Bias due to missing data	Bias in measurement of outcomes	Bias in selection of reported result	Other source of bias
Alimi *et al.*[22] 2020	Serious: very large differences in hernia size, limited characteristics reported; not propensity-matched	Serious: institutional data, not stated whether consecutive series	Low	Low	Moderate: unknown follow-up	Low: complications	Moderate: limited outcomes reported	
Altieri *et al.*[23] 2018	Moderate: differences in ethnicity, sex, BMI; propensity-matched but characteristics not reported	Low: database	Low	Low	Low	Low: complications	Moderate: matched outcomes poorly reported and inconsistent with tables	
Armijo *et al.*[13] 2018	Moderate: similar characteristics except sex and co-morbidities; not propensity-matched	Low: database	Low	Low	Low	Low: narcotic use, complications, cost	Low	
Bittner *et al.*[24] 2018	Serious: differences in co-morbidities, smoking status, sex, hernia size; not-propensity- matched	Low	Low	Low	Low	Low: complications	Moderate: no data on recurrences at 90 days	1st author is consultant for Intuitive
Carbonell *et al.*[25] 2018	Low: similar characteristics, including proportion of TARs performed; propensity-matched	Low: database	Low	Low	Low	Low: complications	Low	6 authors (including 1st author) received honoraria from Intuitive; 2 authors received educational funds from Intuitive
Chen *et al.*[26] 2017	Moderate: similar characteristics except for sex; not propensity-matched	Low	Low	Low	Low	Low: complications, recurrence	Low	
Coakley *et al.*[14] 2017	Low: similar baseline characteristics; not propensity-matched	Low: database	Low	Low	Low	Low: complications, cost	Low	
Dauser *et al.*[27] 2020	Moderate: similar baseline characteristics except sex; not propensity-matched	Serious: institutional data, not stated whether consecutive series	Low	Low	Low	Low: complications	Low	
Gonzalez *et al.*[28] 2015	Low: similar baseline characteristics; not propensity-matched	Low	Low	Low	Moderate: unknown follow-up	Low: complications, recurrence	Low	
Guzman-Pruneda *et al.*[12] 2020	Serious: large difference in sex, smoking status, hernia size; not propensity-matched	Low: database	Low	Low	Low	Low: complications, recurrence Moderate: QoL	Low	Operative techniques (e.g., drain placement) were significantly different between comparison groups
Khorgami *et al.*[29] 2019	Serious: unable to assess characteristics, as data were	Low: database	Low	Low	Low	Low: LOS, cost	Serious: no other outcomes besides LOS	

(continued)

Table 4. (continued)

Reference	Confounding	Selection bias	Bias in measurement classification of interventions	Bias due to deviations from intended interventions	Bias due to missing data	Bias in measurement of outcomes	Bias in selection of reported result	Other source of bias
	pooled for multiple procedures; not propensity-matched							
LaPinska et al.[30] 2020	Low: similar baseline characteristics with propensity matching	Low: database	Low	Low	Moderate: 83–85% short-term follow-up rates	Low: complications	Low	1st author receives personal fees from Intuitive; Intuitive funded independent editorial support and data analysis
Lu et al.[31] 2019	Moderate: similar baseline characteristics except for sex and co-morbidities; not propensity-matched	Low	Low	Low	Serious: large difference in 1-year follow-up rates between groups	Low: complications, recurrence	Low	Senior author has received honoraria for speaking engagements and consulting for Intuitive
Martin-del-Campo et al.[32] 2018	Low: similar baseline characteristics except for ASA; propensity-matched for hernia size	Low	Low	Low	Low	Low: complications	Low	2 authors are consultants for Intuitive
Mudyanadzo et al.[33] 2020	Serious: baseline characteristics not reported; not propensity-matched	Serious: institutional data, not stated whether consecutive series	Low	Low	Low	Low: pain, narcotic use	Low	
Nguyen et al.[34] 2019	Moderate: similar characteristics except hernia size; not propensity-matched	Serious: institutional data, not stated whether consecutive series	Low	Low	Low	Low: complications	Low	
Reeves et al.[35] 2020	Moderate: similar characteristics except certain co-morbidities (i.e., diabetes); not propensity-matched	Serious: institutional data, not stated whether consecutive series	Low	Low	Low	Low: complications	Low	Large difference in postoperative drain placement between comparisons
Song et al.[36] 2017	Moderate: characteristics not explicitly reported; propensity-matched	Low: database	Low	Low	Low	Low: complications, narcotic use, cost	Low	
Tan et al.[37] 2018	Serious: significantly different age, other characteristics not explicitly reported; not propensity-matched	Serious: institutional data, not stated whether consecutive series	Low	Low	Low	Low: cost	Low	
Walker et al.[38] 2018	Moderate: similar baseline characteristics except for sex; propensity-matched except for sex, and matched characteristics not reported	Serious: institutional data, not stated whether consecutive series	Low	Low	Moderate: unknown follow-up	Low: complications, recurrence	Moderate: matched outcomes only reported selectively	2 authors (including senior author) receive honoraria to proctor for Intuitive

(continued)

Table 4. (continued)

Reference	Confounding	Selection bias	Bias in measurement classification of interventions	Bias due to deviations from intended interventions	Bias due to missing data	Bias in measurement of outcomes	Bias in selection of reported result	Other source of bias
Warren *et al.*[39] 2017	Serious: similar characteristics except for sex, recurrent hernia, and whether TAR performed concurrently; not propensity-matched	Low: database	Low	Low	Low	Low: narcotic use, complication	Low	1st and senior authors are speakers for Intuitive
Zayan *et al.*[40] 2019	Serious: difference in sex, BMI, smoking status, baseline QoL; not propensity-matched	Serious: institutional data, not stated whether consecutive series	Low	Low	Moderate: unknown follow-up	Low: recurrence Moderate: QoL	Moderate: no outcomes relating to other complications	

ROBINS-I, Risk Of Bias In Non-Randomized Studies of Interventions; TAR, transversus abdominis release; Qol, quality of life; LOS, length of hospital stay.

Table 5 Intraoperative outcomes in studies comparing robotic with open surgery

Reference	Intraoperative outcomes					
	Duration of operation (min)*			Intraoperative complications (%)		
	Robotic	Open	P	Robotic	Open	P
Studies with propensity matching						
Carbonell *et al.*[25]	> 2 h: 45.1%	> 2 h: 12.6%	< 0.001	1.8	1.4	1.000
Martin-del-Campo *et al.*[32]	299(95)	211(63)	< 0.001	0	0	1.000
Song *et al.*[36]‡	231 (101)	163 (101)	< 0.001	1.0	1.0	1.000
Studies without propensity matching						
Bittner *et al.*[24]	365(78)	287(121)	< 0.010	0	5.3	0.57¶
Dauser *et al.*[27]	253.5 (158–380)†§	211.5 (112–303)†§	0.085	–	–	–
Guzman-Pruneda *et al.*[12]	>4 h: 33%	>4 h: 18%	0.010	0	0	1.000
Nguyen *et al.*[34]‡	272.1	206.5	< 0.001	–	–	–
Reeves *et al.*[35]	260.0(78.9)	185.7(64.5)	0.017	–	–	–

*Values are mean(s.d.) unless indicated otherwise; †values are median (range). ‡Conference abstract. §Skin-to-skin time. ¶Outcome significant when risk difference calculated.

Table 6 Intraoperative outcomes of robotic *versus* laparoscopic surgery

Reference	Intraoperative outcomes					
	Duration of operation (min)*			Intraoperative complications (%)		
	Robotic	Laparoscopic	P	Robotic	Laparoscopic	P
RCTs						
Olavarria *et al.*[20]	141(56)§	77(37)§	< 0.001	–	–	–
Petro *et al.*[21]	146 (123–192)†	94 (69–116)†	< 0.001	5.1	5.6	> 0.99
Studies with propensity matching						
LaPinska *et al.*[30]	>2 h: 42.9%	>2 h: 21.5%	< 0.001	0.98	1.3	0.591
Song *et al.*[36]¶	231(101)	169(108)	< 0.001	1.1	4.3	1.000
Studies without propensity matching						
Chen *et al.*[26]	156.6 (77–261)‡	65.9 (25–128)‡	< 0.001	–	–	–
Gonzalez *et al.*[28]	107.6(33.9)§	87.9(53.1)§	0.012	–	–	–
Lu *et al.*[31]	174.7(44.9)	120.4(35.0)	< 0.001	–	–	–
Walker *et al.*[38]#	116.9(47.9)§	98.7(56.6)§	0.03	–	–	–
Zayan *et al.*[40]	139 (108–186)†	86 (67–104)†	0.009	–	–	–

*Values are mean(s.d.) unless indicated otherwise; values are †median (i.q.r.) and ‡median (range). §Skin-to-skin time. ¶Conference abstract. #Unmatched data presented, as study propensity-matched for limited outcomes.

Information System Pain Intensity short form 3a; however, there was no difference in any of the other reported pain metrics in this trial. One non-matched study[33] reported a reduced narcotic requirement rate at 6–8 weeks after robotic VHR. The remaining three studies[13,20,36], including one RCT and one matched study, did not show differences in change in pain rating from baseline, patient-controlled analgesia use, rate of opiate prescription, or perioperative analgesia between approaches.

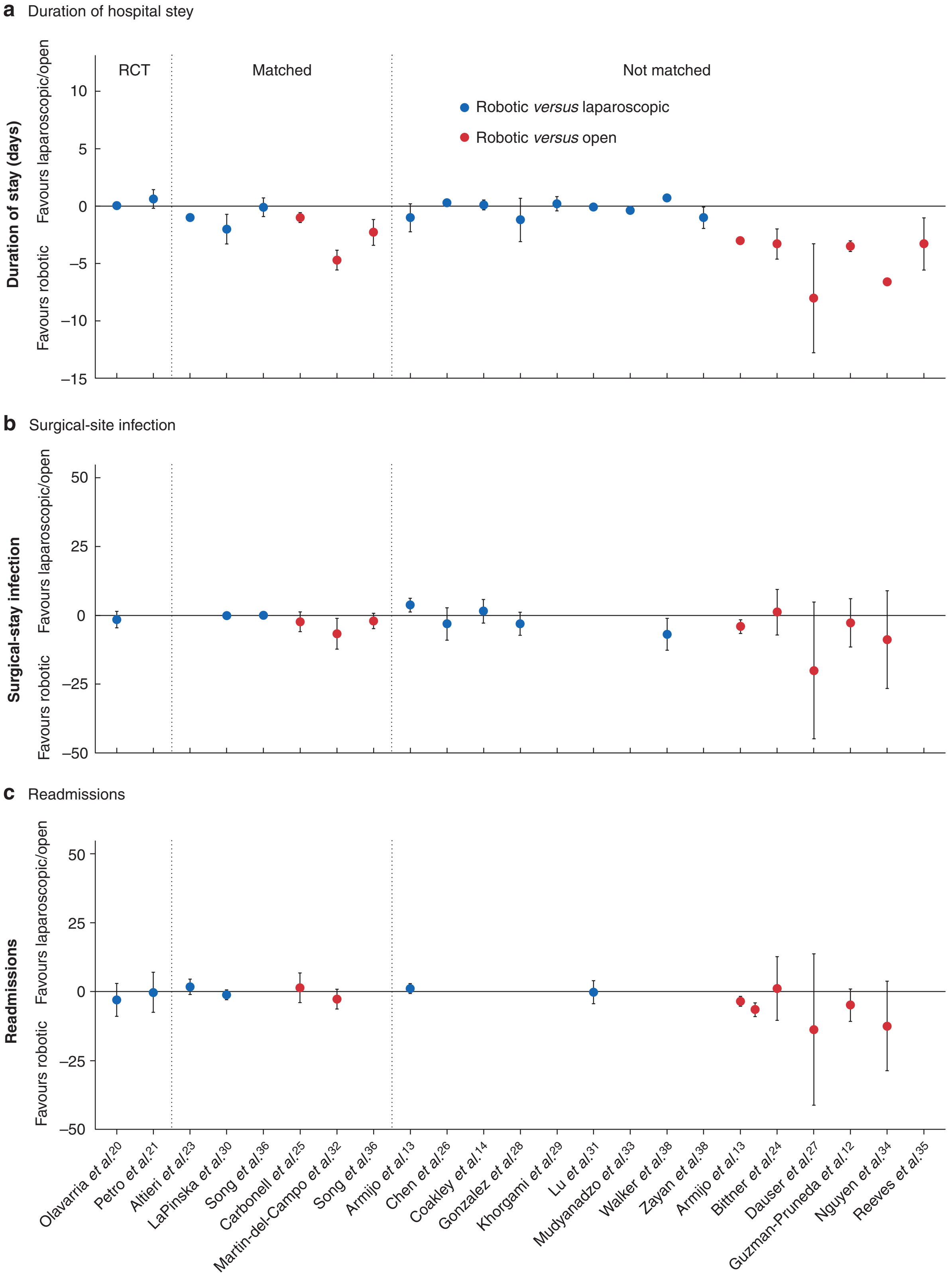

Fig. 2 Forest plot of short-term postoperative outcomes

a Duration of hospital stay, **b** surgical-site infection, and **c** readmission rates. The point estimate for the risk and mean differences are plotted with 95 per cent confidence intervals for robotic ventral hernia repair *versus* laparoscopic or open approaches.

Table 7 Short-term postoperative outcomes of robotic *versus* open surgery

Reference	Duration of hospital stay (days)*			Surgical-site infection (%)§			Total complications (%)§		
	Robotic	Open	P	Robotic	Open	P	Robotic	Open	P
Studies with propensity matching									
Carbonell *et al.*[25]	2 (1–3)†	3 (2–5)†	< 0.001	2	4	0.5	29.7	43.2	–#
Martin-del-Campo *et al.*[32]	1.3(1.3)	6(3.4)	< 0.001	0	6.6	0.106#	0	17.1	0.007
Song *et al.*[36]¶	3.0(2.4)	5.3(5.2)	0.003	0	2.1	0.50	17.7	39.6	0.001
Studies without propensity matching									
Armijo *et al.*[13]	2 (1–4)†	5 (3–8)†	< 0.050	1.7 (0.8, 3.4)	2.8 (2.7, 3.0)	n.s.#	7.3 (5.1, 10.0)	11.4 (11.1, 11.75)	< 0.050
Bittner *et al.*[24]	3.8(1.5)	7.1(5.4)	< 0.010	3.8	2.6	1.00	19.2	30.2	0.32
Dauser *et al.*[27]	4.5 (2–10)‡	12.5 (6–25)‡	< 0.001	0	20.0	–**	12.5	50.0	–#
Guzman-Pruneda *et al.*[12]	1.5 (1–2.8)†	5 (4–6)†	< 0.010	0	1.5	1	9.5	15.5	–**
Nguyen *et al.*[34]¶	3.0	9.6	< 0.001	3.7	12.5	–**	–	–	–
Reeves *et al.*[35]	3.6(2.1)	6.9(3.6)	0.007	–	–	–	15.4	23.1	0.619

*Values are mean(s.d.) unless indicated otherwise; values are †median (i.q.r.) and ‡median (range); §values in parentheses are 95 per cent confidence intervals. ¶Conference abstract. n.s., Not significant. #Outcome significant when risk difference calculated; **Outcome not significant when risk difference calculated.

Table 8 Short-term postoperative outcomes of robotic *versus* laparoscopic surgery

Reference	Duration of hospital stay (days)*			Surgical-site infection (%)§			Total complications (%)§		
	Robotic	Laparoscopic	P	Robotic	Laparoscopic	P	Robotic	Laparoscopic	P
RCTs									
Olavarria *et al.*[20]	0	0	0.82	0	1.7	1.00	21.5	19.0	0.80
Petro *et al.*[21]	25 h (10–30)†	10 h (8–31)†	0.17	–	–	–	5.1	8.3	> 0.99
Studies with propensity matching									
Altieri *et al.*[23]	Median difference (robotic *versus* laparoscopic): −1 day		< 0.001	–	–	–	14.60	20.35	0.013
LaPinska *et al.*[30]	2(7)	4(13)	< 0.001	0.76	0.97	0.716	10.5	11.5	0.613
Song *et al.*[36]¶	3.0(2.4)	3.2(3.0)	0.67	0.0	0.0	1.00	17.0	24.5	0.21
Studies without propensity matching									
Armijo *et al.*[13]	2 (1–4)†	3 (2–4)†	n.s.	1.7 (0.8, 3.4)	0.7 (0.5, 0.9)	< 0.05	7.3 (5.1, 10.1)	3.5 (3.1, 4.0)	< 0.050
Chen *et al.*[26]	0.49 (0–3)‡#	0.21 (0–1)‡#	0.09	0	3.03	0.458	7.7	9.1	1
Coakley *et al.*[14]	3.5(3.6)	3.4(2.6)	0.211	0.85	0.47	0.234	20.24	18.73	–††
Gonzalez *et al.*[28]	2.5(4.1)	3.7(6.6)	0.461	2	0	–††	3.0	10.4	0.084
Khorgami *et al.*[29]	2.9(3.1)	2.7(1.9)	–††	–	–	–	–	–	–
Lu *et al.*[31]	0.1(0.5)	0.2(0.9)	0.294	–	–	–	2.3	9.2	0.046
Mudyanadzo *et al.*[33]	1.3(0.1)	1.7(0.2)	n.s.‡‡	–	–	–	–	–	–
Walker *et al.*[38]**	1.4(0.4)	0.7(0.3)	0.09‡‡	0	6.8	< 0.01	–	–	–
Zayan *et al.*[40]	22.1 (9.4–33.7) h†	46.3 (26.3–65.6) h†	0.044	–	–	–	–	–	–

*Values are mean(s.d.), unless indicated otherwise; values are †median (i.q.r.) and ‡median (range); §values in parentheses are 95 per cent confidence intervals. ¶Conference abstract. #Reported only for those who required admission in the robotic (14) and laparoscopic (7) groups. n.s., Not significant. **Unmatched data presented, as study propensity-matched for limited outcomes. ††Outcome significant when risk difference calculated; ‡‡Outcome not significant when risk difference calculated.

Hernia recurrence

One non-matched study[12] evaluated 1-year recurrence rates in robotic and open VHR, and reported no difference.

Of the seven studies assessing recurrence rates after robotic and laparoscopic repairs, study-specific follow-up varied from 1 month to nearly 2 years. One matched study[38] with a mean follow-up of approximately 6 weeks found a decrease in recurrence rate in the robotic cohort. However, the remaining six[20,22,26,28,31,40], including one RCT, found no differences in hernia recurrence rates.

Cost

Nine studies[13,14,20,21,27,29,36,37,39] reported cost data for robotic VHR compared with laparoscopic and open approaches (*Table 9*). One study[37] reported cost data only and no clinical outcomes; one database study[39] was included for cost outcomes only, and excluded from analyses of clinical outcomes owing to overlapping clinical data. Three studies[13,27,36] compared robotic with open VHR, and eight[13,14,20,21,29,36,37,39] compared robotic with laparoscopic surgery. Of the three studies comparing robotic with open VHR, one[13] found the robotic approach to be more expensive, whereas the two others[27,36] reported no difference in costs between the two approaches. Five studies[13,14,20,21,29], including two RCTs, found the robotic approach to be more expensive than laparoscopic surgery, one[39] reported that the robotic approach showed a non-significant trend towards higher costs than laparoscopy, and two[36,37] found that robotic surgery and laparoscopy were no different with respect to costs.

Table 9 Cost outcomes

Reference	Source of cost data	Cost outcomes (€)*				
		Type of cost data	**Robotic**	**Laparoscopic**	**Open**	**P**
RCTs						
Olavarria *et al.*[20]	Costs including all patient visits, admissions, and procedural costs from operation through first 90 postoperative days came from hospital administration accounting system. Cost did not include surgeons' fees or initial acquisition cost of robotic or laparoscopic platforms	Mean costs	19 038 (5854)	15 546 (6763)	–	0.004
Petro *et al.*[21]	Values for cost reported as ratios. Total cost includes OR cost (as calculated by cost per minute of OR time required for the procedure) and disposable/reusable cost, which was calculated to include disposable materials as well as reusable materials including robotic instruments	Disposable/reusable median cost ratio	0.97 (0.85–1.51)†	1.00 (0.87–1.19)†	–	0.60
		OR time cost ratio	1.25 (0.98–1.49)†	0.85 (0.67–1.00)†	–	< 0.001
		Total cost ratio	1.13 (0.90–1.52)†	0.97 (0.85–1.16)†	–	0.03
Studies with propensity matching						
Song *et al.*[36]¶	Total cost included direct cost and overhead cost, adjusted for inflation to 2015 US dollars	Total cost	12 422	–	12 989	n.s.
			12 562	12 908	–	n.s.
Studies without propensity matching						
Armijo *et al.*[13]	Ratio of cost-to-charge method applied for estimating cost of patient care	Total direct cost	12 000 (8400, 16 800)‡	8400 (6000, 10 800)‡	10 800 (7200, 19 200)‡	< 0.050#
Coakley *et al.*[14]	Total hospital charges	Adjusted mean charges (controlling for CCI, geography, public *versus* private, etc.)	73 446(1717)	50 293(310)	–	< 0.001
Dauser *et al.*[27]	Procedure-related costs calculated exact to the minute	Total procedure-related costs	5394.41	–	1987.19	–
	Cost unit accounting for the postoperative inpatient stay done using data provided by controlling department. Earnings including subsidies, non-medical material costs, expenditures for physicians, nursing, medical technical assistance, pharmaceuticals, third-party suppliers, and maintenance were added. In addition, apportionment of indirect costs for ICU, operating theatre, radiology, outpatient clinic, management and administration were priced in for full cost accounting for inpatient stay in surgical ward. Costs per day in this setting amount to €493.63	Cost of inpatient stay	2714.53	–	6662.93	–
		Total cost	8108.93	–	8650.12	–
Khorgami *et al.*[29]	Hospital total charges converted to cost estimates using hospital specific cost-to-charge ratios provided by HCUP. Admissions with total charges below 0.1th percentile or above 99.9th percentile were considered outliers and excluded from analysis	Average cost estimate	16 093(6648)	12 887(5774)	–	< 0.050

(continued)

Table 9. (continued)

Reference	Source of cost data	Cost outcomes (€)*				
		Type of cost data	Robotic	Laparoscopic	Open	P
Tan *et al.*[37]¶	Primary outcome: disposable operating room costs	Median OR costs	3714 (3 532–3988)†	4069 (3204–5074)†	–	0.056
	Secondary outcomes: technical direct costs such as costs from laboratory or pharmacy	Median total variable costs	5234 (4571–6433)†	5461 (4234–7399)†	–	0.609
Warren *et al.*[39]	No details provided	Mean direct hospital cost	23 438	16 732	–	0.07

*Values are mean(s.d.) unless indicated otherwise; †values are median (i.q.r.); ‡values in parentheses are 95 per cent confidence intervals. Original charges in US dollars were converted to euros at an exchange rate of US $1.2 to €1. ¶Conference abstract. OR, operating room; n.s., not significant; CCI, Charlson Co-morbidity Index; HCUP, Healthcare Cost and Utilization Project; #Two-way comparisons of robotic *versus* open and robot *versus* laparoscopic.

Discussion

Overall, the evidence for the comparison between robotic and open VHR had low certainty (*Table 10*). Robotic VHR has a longer operating time and shorter hospital stay than open repair, supported by evidence of moderate certainty. There is low certainty that robotic VHR is associated with fewer transfusions and very low certainty that it is associated with a decreased total complication rate compared with open repair. There is low or very low certainty of evidence for no difference in intraoperative complications, SSI, readmissions, hernia recurrence, and cost.

There is high certainty of evidence that robotic VHR takes longer than laparoscopic repair, with no evidence of any difference in length of hospital stay or intraoperative complications, SSI, readmissions, or hernia recurrence between these approaches. There is low certainty that robotic VHR has greater costs than laparoscopic repair. There is low or very low certainty of evidence for no difference in rates of conversion to open surgery, transfusion, mortality, and total complications, or pain. Based on current data, there is no high-quality evidence that either approach is superior to the other with regard to clinical outcomes, excluding duration of operation.

The longer operating time for robotic VHR compared with open surgery or laparoscopic VHR is consistent with similar findings for inguinal hernia repair and cholecystectomy[41,42]. This is likely related to a variety of factors, including robot docking, surgeon and staff efficiency, learning curve, and patient selection. Most studies in the present review acknowledged the learning curve as a potential contributing factor; however, only one[27] evaluated operative times longitudinally, which decreased after the first six procedures.

Two matched studies reported lower transfusion rates associated with robotic VHR compared with open surgery. This may be due to magnified visualization, smaller cut surfaces, and intra-abdominal pressure tamponade, although the certainty of evidence is limited as transfusions were rare. This topic should be explored further, as transfusion is a critical clinical outcome and determinant of resource use[43].

Robotic VHR is also associated with shorter hospital stay compared with open surgery, probably reflecting earlier mobilization and faster functional recovery. Earlier functional recovery may contribute to the decreased complications of robotic VHR compared with open surgery.

The European and Americas Hernia Societies guidelines[6] do not recommend a preferred surgical approach for minimizing pain outcomes. Pain assessments varied widely in the present review. Small differences in pain outcomes may not have been detected because of lack of standardized reporting. A meta-epidemiological study[44] noted that effect estimates for subjective outcomes were exaggerated when studies had unclear allocation concealment or lacked blinding, such as in the included RCTs, yet trials with objective outcomes had little evidence of bias. Future work should report objective measures consistently. Chronic pain should be evaluated with follow-up of at least 6 months and include assessments for pain requiring intervention.

This review has limitations. Only two RCTs met the inclusion criteria, and a third limited RCT abstract was excluded. The remaining data were observational, although six of the studies were propensity-matched, the result of non-matched studies were mostly congruent with matched and randomized data. Conclusions about the robotic approach compared with open VHR were based only on observational data. Although the earliest RCTs[20,21] looking at robotic VHR were included, these patients had small hernias (3–5 cm) that were repaired mostly on an outpatient basis (median hospital stay 0–1 days), reflecting overall lower complexity. Therefore, the findings may not be generalizable to larger (over 10 cm) and more complex hernias, for which a minimally invasive approach may be less appropriate. Most studies reported only short-term outcomes, and the RCTs were underpowered to detect differences in pain or recurrence. Technical factors, such as hernia size, primary *versus* recurrent hernia, operative urgency, technique, mesh fixation, and fascial closure, were reported inconsistently. Hernia recurrence was reported infrequently, with only one study evaluating the robotic *versus* open approaches. Follow-up for hernia recurrence ranged from 47 days to nearly 2 years. Current guidelines for inguinal hernia repair recommend 3–5-year follow-up for recurrences[44]; however, that time frame is often not feasible (for example because of patient attrition or high cost) and follow-up should be standardized to at least 1 year. Seven of 22 studies disclosed financial relationships with Intuitive Surgical, introducing potential for author bias (*Tables 1* and *3*).

The methodology of the cost studies was limited, specifically how values were derived. Cost estimates for the robotic approach varied considerably (from €5234 to 73 446). The majority of studies did not define the type of cost or charge, time frame, or items included in cost estimates, follow cost-reporting guidelines[45], or report staff costs—the largest component of operative costs[8]. Several studies relied on administrative databases and used cost-to-charge ratios to estimate hospital costs[13,29,46], which are prone to bias[47]. Furthermore, the overall cost of care was not available, and no formal cost-effectiveness analyses were performed.

Randomized or matched data are still needed to account for patient and technical factors and, particularly, to evaluate large, complex hernias. Standardization of outcome measurements

Table 10 GRADE summary of findings and certainty of evidence

	Study limitations	Consistency	Directness	Precision	Certainty of evidence
Intraoperative outcomes					
Duration of operation	Unmatched observational studies: high				
Robotic > open		Consistent	Direct	Precise	Moderate
Robotic > laparoscopic	Matched observational studies: moderate	Consistent	Direct	Precise	High
	RCTs: moderate				
Intraoperative complications	Unmatched observational studies: high				
Robotic = open		Consistent	Direct	Imprecise	Low
Robotic = laparoscopic	Matched observational studies: moderate	Consistent	Direct	Imprecise	Moderate
	RCTs: moderate				
Transfusion	Matched observational studies: moderate				
Robotic < open		Consistent	Direct	Imprecise	Low
Robotic = laparoscopic		Inconsistent	Direct	Imprecise	Very low
Conversion to open surgery	Unmatched observational studies: high				
Robotic = laparoscopic	Matched observational studies: moderate	Inconsistent	Direct	Imprecise	Low
	RCTs: moderate				
Postoperative short-term outcomes					
Length of hospital stay	Unmatched observational studies: high				
Robotic < open		Consistent	Direct	Precise	Moderate
Robotic = laparoscopic	Matched observational studies: moderate	Inconsistent	Direct	Precise	Moderate
	RCTs: moderate				
Surgical-site infection	Unmatched observational studies: high				
Robotic = open		Consistent	Direct	Imprecise	Low
Robotic = laparoscopic	Matched observational studies: moderate	Consistent	Direct	Imprecise	Moderate
	RCTs: moderate				
Readmissions	Unmatched observational studies: high				
Robotic = open		Consistent	Direct	Imprecise	Low
Robotic = laparoscopic	Matched observational studies: moderate	Consistent	Direct	Imprecise	Moderate
	RCTs: moderate				
Mortality	Unmatched observational studies: high				
Robotic = open/laparoscopic	Matched observational studies: moderate	Consistent	Direct	Imprecise	Low
Total complications	Unmatched observational studies: high				
Robotic < open		Inconsistent	Indirect	Imprecise	Very low
Robotic = laparoscopic	Matched observational studies: moderate	Inconsistent	Indirect	Imprecise	Low
	RCTs: moderate				
Postoperative functional outcomes					
Pain	Unmatched observational studies: high				
Robotic = open		Inconsistent	Indirect	Imprecise	Very low
Robotic = laparoscopic	Matched observational studies: moderate	Inconsistent	Indirect	Imprecise	Low
	RCTs: moderate				
Hernia recurrence	Unmatched observational studies: high				
Robotic = open		–	Direct	Imprecise	Very low
Robotic = laparoscopic	Matched observational studies: moderate	Consistent	Direct	Imprecise	Moderate
	RCTs: moderate				
Cost					
Cost	Unmatched observational studies: high				
Robotic = open		Inconsistent	Indirect	Imprecise	Very low
Robotic > laparoscopic	Matched observational studies: moderate	Inconsistent	Indirect	Imprecise	Low
	RCTs: moderate				

GRADE, Grading of Recommendations, Assessment, Development, and Evaluation.

and long-term follow-up, and more detailed economic analyses are all necessary.

Taken the high morbidity rates after open VHR, particularly for large complex hernias, the robotic platform may be an effective minimally invasive approach capable of delivering genuine clinical benefit. Randomized studies of better quality are needed.

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Supplementary material

Supplementary material is available at *BJS Open* online.

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