Robot-assisted Procedures in General Surgery: Cholecystectomy, Inguinal and Ventral Hernia Repairs

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PREFACE

The VA Evidence Synthesis Program (ESP) was established in 2007 to provide timely and accurate syntheses of targeted healthcare topics of importance to clinicians, managers, and policymakers as they work to improve the health and healthcare of Veterans. These reports help:

- Develop clinical policies informed by evidence;
- Implement effective services to improve patient outcomes and to support VA clinical practice guidelines and performance measures; and
- Set the direction for future research to address gaps in clinical knowledge.

The program is comprised of 4 ESP Centers across the US and a Coordinating Center located in Portland, Oregon. Center Directors are VA clinicians and recognized leaders in the field of evidence synthesis with close ties to the AHRQ Evidence-based Practice Center Program and Cochrane Collaboration. The Coordinating Center was created to manage program operations, ensure methodological consistency and quality of products, and interface with stakeholders. To ensure responsiveness to the needs of decision-makers, the program is governed by a Steering Committee comprised of health system leadership and researchers. The program solicits nominations for review topics several times a year via the program website.

Comments on this evidence report are welcome and can be sent to Nicole Floyd, Deputy Director, ESP Coordinating Center at Nicole.Floyd@va.gov.

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This topic was developed in response to a nomination by Dr. Mark Wilson, National Director of Surgery, and Dr. William Gunnar, Executive Director, National Center for Patient Safety and former National Director of Surgery. The scope was further developed with input from the topic nominators (*ie*, Operational Partners), the ESP Coordinating Center, the review team, and the technical expert panel (TEP).

In designing the study questions and methodology at the outset of this report, the ESP consulted several technical and content experts. Broad expertise and perspectives were sought. Divergent and conflicting opinions are common and perceived as healthy scientific discourse that results in a thoughtful, relevant systematic review. Therefore, in the end, study questions, design, methodologic approaches, and/or conclusions do not necessarily represent the views of individual technical and content experts.

The authors gratefully acknowledge Roberta Shanman, Jon Bergman, and the following individuals for their contributions to this project:

Operational Partners

Operational partners are system-level stakeholders who have requested the report to inform decision-making. They recommend Technical Expert Panel (TEP) participants; assure VA relevance; help develop and approve final project scope and timeframe for completion; provide feedback on draft report; and provide consultation on strategies for dissemination of the report to field and relevant groups.

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Technical Expert Panel (TEP)

To ensure robust, scientifically relevant work, the TEP guides topic refinement; provides input on key questions and eligibility criteria, advising on substantive issues or possibly overlooked areas of research; assures VA relevance; and provides feedback on work in progress. TEP members are listed below:

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Peer Reviewers

The Coordinating Center sought input from external peer reviewers to review the draft report and provide feedback on the objectives, scope, methods used, perception of bias, and omitted evidence. Peer reviewers must disclose any relevant financial or non-financial conflicts of interest. Because of their unique clinical or content expertise, individuals with potential conflicts may be retained. The Coordinating Center and the ESP Center work to balance, manage, or mitigate any potential nonfinancial conflicts of interest identified.

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INTRODUCTION

General surgery procedures make up a large volume of operations performed in the US. For example there are approximately 1 million cholecystectomies and 800,000 ventral and inguinal hernia cases performed each year. Within this field we are experiencing dramatic recent growth in the number of robot-assisted cases. Questions about the utility of robot-assisted surgery as compared to laparoscopic and open surgery persist. In particular, does the use of the robot translate to better or similar clinical outcomes for patients? Are operating room times and length of stay comparable or improved with use of robot versus laparoscopic or open techniques? And what are costs of robot-assisted surgery and are they justified? Yet there is no consensus or guidelines on when to use which surgical approach and decisions are left up to individual practitioners or hospital leadership. To help clinicians, patients, and policymakers better assess the appropriateness of robot-assisted compared to other surgical approaches, we were asked to conduct a systematic review of the literature on 3 of the most common general surgery operations: cholecystectomy, inguinal hernia repair, and incisional hernia repair.

METHODS

This topic was developed in response to a nomination by Dr. Mark Wilson, National Director of Surgery, and Dr. William Gunnar, Executive Director, National Center for Patient Safety and former National Director of Surgery. Key questions were then developed with input from the topic nominator, the ESP coordinating center, the review team, and the technical expert panel (TEP).

The Key Questions are:

KQ1A: What is the clinical effectiveness of robot-assisted surgery compared to conventional laparoscopic surgery for cholecystectomy?

KQ2A: What is the cost-effectiveness of robot-assisted surgery compared to conventional laparoscopic surgery for cholecystectomy?

KQ1B: What is the clinical effectiveness of robot-assisted surgery compared to conventional laparoscopic or open surgery for inguinal hernia repair?

KQ2B: What is the cost-effectiveness of robot-assisted surgery compared to conventional laparoscopic or open surgery for inguinal hernia repair?

KQ1C: What is the clinical effectiveness of robot-assisted surgery compared to conventional laparoscopic or open surgery for ventral hernia surgery?

KQ2C: What is the cost-effectiveness of robot-assisted surgery compared to conventional laparoscopic or open surgery for ventral hernia surgery?

Data Sources and Searches

We conducted separate searches for cholecystectomy, inguinal hernia repair, and ventral hernia repair. All searches included PubMed, Embase, and Cochrane (all databases) from 2010 to March 2020. For inguinal and ventral hernia repairs, Medline was also searched from 2010 to 2020.

Study Selection

Studies were included if they were randomized control trials or observational studies comparing robot-assisted surgery with either conventional laparoscopic or open surgical approaches for either of the included surgical procedures. We included all randomized controlled trials (RCTs) regardless of outcomes studied. We did not have sample size restrictions for cholecystectomy, but excluded studies with sample size <10 for inguinal and ventral hernia repairs. Specifically, each comparative arm needed to have a sample of more than 10. The cholecystectomy technique is very standard (with the exception of the number of ports used). However, both hernia repair techniques are widely variable including factors such as mesh location, size of hernia, type of sutures, use of tacks, use of sutureless mesh, etcetera, and these continue to evolve. These factors were not consistently reported. As such, we made the decision that the small studies (<10 sample size) would have the potential for substantial unmeasured bias.

We also included publications of cost-effectiveness models or cost that compared robot-assisted surgery with laparoscopic or open surgical approaches.

Data Abstraction and Quality Assessment

We abstracted data on the following: study design, patient characteristics, sample size, intraoperative outcomes, postoperative outcomes, long-term functional outcomes, duration of follow-up, and data needed for the Cochrane Risk of Bias tool or Cochrane Risk of Bias In Non-randomized Studies – of Interventions (ROBINS-I).

Data Synthesis and Analysis

Because the few RCTs were too heterogeneous, we did not conduct a meta-analysis of trials. Additionally, the observational studies were too clinically heterogeneous to support meta-analysis; hence, our synthesis is narrative. We assessed robot-assisted and laparoscopic approach for cholecystectomy, as open cholecystectomy is typically performed for cancer pathology or in the setting of significant inflammation or adhesive disease. We assessed robot-assisted, laparoscopic, and open approaches for inguinal and ventral hernia repairs. Of note, cholecystectomy (for benign disease) and most inguinal hernias are performed as outpatient surgery.

Further, since there were limited RCTs and the observational studies had considerable differences between comparative arms (within and between studies), specific considerations for each of the 3 operations was warranted, in order to lessen confounding factors. Specifically, we needed to account for variations in patient factors and surgical techniques, which could impact clinical outcomes. For example, if a robot-assisted surgery study arm had a higher number of bilateral hernias than the laparoscopic group, this could account for longer operative times or higher rate of complications. Studies that performed matching (propensity matching) in our review would account for a number of important variables but typically did not control for all relevant patient or technical factors (ie, extent of fascial closure, hernia size, etc). Of note, our research team made the following judgments to facilitate comparisons of the studies identified (which were mainly observational data).

- For cholecystectomy, we present the data by grouping studies based on the number of surgical access ports used:
    - *robot single-port compared to laparoscopic single-port or robot multi-port compared to laparoscopic multi-port;*
    - *robot single-port compared to laparoscopic multi-port;*
    - *robot compared to laparoscopic for those with unknown number of ports* (in terms of outcomes).

  We did not identify any study reporting robot multi-port to laparoscopic single-port.

- For inguinal hernia repair, we present the data by grouping studies where hernia laterality (unilateral or bilateral) was:
    - *known and at least <25% between comparative arms, or outcomes reported by laterality*;
    - *laterality not known.*

- For ventral hernia repair, we present the data by grouping studies that:
    - *attempted matching on patient, hernia or technique factors;*
    - *matching not performed.*

We used the criteria of the Grading of Recommendations Assessment, Development and Evaluation (GRADE) working group to assess the certainty of evidence across studies.

RESULTS

Results of Literature Search

For cholecystectomy, we identified 887 potentially relevant citations, of which 169 were included for abstract screening. A total of 47 publications were identified at full-text review as meeting initial inclusion criteria: RCT with cost and clinical data (n=1), RCTs with clinical data only (n=3), observational studies with cost data only (n=3), observational studies with clinical outcomes only (n=25), and observational studies with both clinical and cost data (n=15).

For inguinal hernia repair, we identified 3,319 potentially relevant citations and 9 publications recommended by experts. From these, 185 were included for abstract screening. A total of 23 publications were identified at full-text review as meeting initial inclusion criteria: RCT with clinical and cost data (n=1), observational studies with clinical outcomes only (n=18), and observational studies with both clinical and cost data (n=4).

For ventral hernia repair, we identified 3,458 potentially relevant citations and 5 publications recommended by experts. From these, 369 were included for abstract screening. A total of 22 publications were identified at full-text review as meeting initial inclusion criteria: RCT with clinical data only (n=1), observational study with cost data only (n=1), observational studies with clinical data only (n=15), and observations studies with both clinical and cost data (n=5).

Summary of Results for Key Questions

KQ1A: What is the clinical effectiveness of robot-assisted surgery compared to conventional laparoscopic surgery for cholecystectomy?

In general, operative room (OR) time was longer in patients treated with robot-assisted cholecystectomy compared to laparoscopic cholecystectomy. While not always statistically significant, data are consistent across RCTs and observational studies. There was no evidence of differences in total intraoperative complications or conversions, and most studies had point estimates close to the null value. Only 6 studies reported common bile duct injuries, and there was no difference between robot-assisted cholecystectomy and laparoscopic cholecystectomy. There was no evidence that conversion rates were different between the approaches, regardless of the port comparisons. Most studies did not demonstrate a significant difference in length of stay (LOS), postoperative complications, or surgical site infections (SSI). However, there may be a trend toward lower LOS for single-port robot-assisted cholecystectomy to single-port laparoscopic approach. Postoperative pain was reported inconsistently among the studies and did not demonstrate a pattern favoring robot-assisted or laparoscopic surgery. There may also be a trend toward a lower readmission rate for the robot-assisted approach. The rate of developing a postoperative incisional hernia may be higher in single-port robot-assisted cholecystectomy. All of the studies that demonstrated a statistically significant difference in incisional hernia rate compared single-port robot-assisted cholecystectomy to multi-port laparoscopic cholecystectomy. Studies that compared single-port robot-assisted cholecystectomy and single-port laparoscopic cholecystectomy or multi-port robot-assisted to multi-port laparoscopic-assisted did not report different rates for incisional hernias. This may be because the single-port approach with robot-assisted cholecystectomy or laparoscopic cholecystectomy involves a larger incision and has a higher risk for developing an incisional hernia.

KQ2A: What is the cost-effectiveness of robot-assisted surgery compared to conventional laparoscopic surgery for cholecystectomy?

While there are a number of studies comparing the cost-effectiveness of robot-assisted versus laparoscopic surgery for cholecystectomy, all had significant limitations, primarily surrounding the cost methodology. None were formal cost-effectiveness analysis studies. Nevertheless, there was an almost unanimous finding, including in the randomized data, that the robot-assisted approach is more expensive than the laparoscopic approach. We therefore have moderate certainty that robot-assisted surgery is more expensive than laparoscopic cholecystectomy. How much more expensive is not known with precision. The lack of cost-effectiveness studies suggests that weighing the balance between the added cost against possible benefits and risks of the robot-assisted approach is not possible

KQ1B: What is the clinical effectiveness of robot-assisted surgery compared to conventional laparoscopic or open surgery for inguinal hernia repair?

Operative room time was longer in patients treated with robot-assisted inguinal hernia repair compared to laparoscopic and open repair, particularly for unilateral repairs. There was no evidence of a difference in conversions for the 3 studies reporting conversion rates between robot-assisted and laparoscopic approaches. In terms of LOS, there may be a signal of a small benefit favoring the robot-assisted approach compared to open surgery for inpatient stays. There does not appear to be a signal of benefit with regard to SSI for the robot-assisted approach compared to laparoscopic or open surgery. There may be a small signal of benefit for lower readmissions with the robot-assisted approach for bilateral and unilateral hernia repairs as compared to open approach. Most studies demonstrated no difference among approaches when assessing complications and postoperative pain. There was no evidence of difference in hernia recurrence among all approaches.

KQ2B: What is the cost-effectiveness of robot-assisted surgery compared to conventional laparoscopic or open surgery for inguinal hernia repair?

Five studies compared costs of robot-assisted to laparoscopic or open surgery for inguinal hernia repair. All had significant limitations, primarily surrounding the cost methodology. Robot-assisted surgery was more expensive in all 5 studies as compared to laparoscopic or open inguinal hernia repair. However, we judged this evidence to be of moderate certainty. Additionally, no formal cost-effectiveness analysis was performed, and thus no definitive conclusion regarding cost can be made.

KQ1C: What is the clinical effectiveness of robot-assisted surgery compared to conventional laparoscopic or open surgery for ventral hernia repair?

Operative room time was significantly longer in robot-assisted ventral hernia repair compared to both the laparoscopic and open approaches in all but 1 of the included studies. There was no evidence of difference in intraoperative complication rate among the approaches. There is a possible trend toward decreased transfusion rate with robot-assisted surgery compared to laparoscopic and open repairs, with 1 study demonstrating a significant difference favoring robot-assisted surgery and another demonstrating no difference. Conversion rate may have a small signal of being lower with robot-assisted surgery compared to the laparoscopic approach. Robot-assisted ventral hernia repair appears to significantly decrease LOS compared to open repair; however, this difference may be less than when compared to laparoscopic repair. There is a likely decrease in postoperative complication rate following robot-assisted repair compared to both open and laparoscopic approaches based on the results of matched studies (unmatched studies do not support this trend). There may be a small signal of decreased SSI rates in the robot-assisted group as compared to the open approach. There is no evidence of difference in the following specific postoperative events: readmission, mortality, or postoperative pain rates among the surgical approaches. Finally, in terms of hernia recurrence, 1 matched study showed decreased rate as compared to laparoscopic surgery and 1 study did not. The 1 matched study for open surgery showed no difference.

KQ2C: What is the cost-effectiveness of robot-assisted surgery compared to conventional laparoscopic or open surgery for ventral hernia repair?

There are a handful of cases comparing the costs of robot-assisted to laparoscopic or open surgery for ventral hernia repair. All had significant limitations, primarily surrounding the cost methodology. However, 4 of the 6 studies reported that the robot-assisted approach was more expensive than either the laparoscopic or open approach (with large effect size) and the other 2 studies reported no difference in cost as compared to laparoscopic repair. As seen for cholecystectomy and inguinal hernia, no cost-effectiveness studies were identified and definitive conclusions cannot be made.

DISCUSSION

Key Findings and Strength of Evidence

Robot-assisted surgery for cholecystectomy, inguinal hernia repair, and ventral hernia repair is associated with longer OR times, in general, and the strength of evidence ranged from high to low, depending on the procedure. The differences are possibly related to the additional docking times needed for the robot-assisted console. Of note, there is variability with how OR time was measured across the studies. Similarly, there is a learning curve effect as surgeons become more experienced on the robot over time, which some of the studies were likely capturing and others specifically addressed. For other intraoperative events, there were small signals noted favoring less transfusions and conversions to open procedure for ventral hernia repair. However, the strength of evidence was low. For postoperative LOS, there were trends favoring each procedure: moderate certainty in evidence for ventral hernia repair, and moderate certainty for LOS for inguinal hernia repair. For inguinal and ventral hernia repairs, there are signals that some postoperative complications may be lower with the robot-assisted approach for these procedures as compared to open. Likewise, there is evidence that a number of other postoperative events are lower for ventral hernia repair – specifically, postoperative complications and SSI (as compared to open approach) – but these both had low certainty of evidence. In general, the certainty of evidence is low or very low, as there were few RCTs. Readmissions may also be lower for robot-assisted approach for cholecystectomy (low certainty of evidence).

On the crucial issues of long-term outcomes, such as recurrences or chronic pain (for the 2 types of hernia repairs), data are too sparse and imprecise to reach any conclusions. Overall, the comparator arms for these procedures were limited by differences in patient factors, hernia factors (*ie*, laterality, hernia size), and varying techniques (*ie*, type of fascial closure).

Cost studies found higher expense associated with robot-assisted surgery, which was consistently reported, but these are limited by the wide variability in the methodologies and definitions used to measure cost. Formal cost-effectiveness for these 3 procedures has not been estimated and definitive conclusions regarding the balance between benefits, risks, and cost cannot be made. If efficiencies in the robot-assisted approach improve over time (as the learning curve is achieved), this in turn may bring down some of the costs. Unfortunately, we are not aware of any robot-assisted cost data within VA, but utilization data are available and this may serve as a first step towards future research in this area.

Applicability

There were a limited number of studies specific to VA populations; 1 was on cholecystectomy, 1 was on inguinal hernia repair, and none on ventral hernia repair. As such, we are unable to make specific conclusions from VA data.

Non-VA studies account for most of our evidence. Applicability of these results to VA populations may depend on both the similarity of the patients studied to VA patients and the experience of the surgical teams using robot-assisted surgery to VA surgical team experience. However, the benefits for robot-assisted approach may still be realized despite patient-level differences (VA patient population has greater burden of comorbidities than the general population), which will need to be confirmed in future studies. Urologic surgery has been widely adopted in the VA, so this experience for the staff may translate into an easy implementation to the robot-assisted general surgery field.

Research Gaps/Future Research

Numerous research gaps are apparent. There is a need for randomized data or propensity matching that addresses patient- and technique-related factors. The variability in the use of the robot-assisted approach based on these factors currently limits the ability to compare across study arms, as variations at baseline or differences in how the operation was performed are large and may likely be responsible for realized clinical differences or lack thereof. Importantly, there are advantages of the robot-assisted approach that are clear and notable – enhanced, three-dimensional visualization, augmented dexterity and range of motion, and reduction of tremor, to name a few. The heterogeneous nature of the studies limited the ability to show how these features translate into better clinical outcomes. Studies that control for key patient factors, case complexity, technical aspects of procedures, and surgeon experience may provide insight into this overarching question. Additionally, adequate long-term follow-up for certain outcomes is greatly needed. Several areas warrant specific discussion.

Surgeon Learning Curve

The surgeon learning curve is a well-characterized surgical concept that has similarly been applied to robot-assisted surgery. As with any new platform, the need for training, practice, and experience is needed. Even open surgical procedures, such as pancreatectomy, suffer from inexperienced surgeons that require tutelage before displaying mastery of a technique. The advent of laparoscopy more than 30 years ago brought this concept more into the forefront and showed the impact of surgeon learning curves on clinical patient outcomes. Likewise, surgeon learning curve for robot-assisted cases is a multifaceted issue. Previous reviews found that the surgeon experience (*ie*, ability as a function of cases completed) is fluid as it has multiple phases and surgeons tend to add increasingly complex patient cases as they gain experience.[1] In our review, we found that 90% of the studies for robot-assisted cholecystectomy acknowledged the possibility of a learning curve; however only 5/46 provided data/assessment (and findings on OR time and incisional hernia occurrence were mixed). A learning curve impact may likely vary by procedure as well. Research assessing surgeon experience needs to include a variety of clinical outcomes, not just efficiency such as OR time. With emerging technologies, research should routinely comment on and address the potential impact the level of experience of the surgeon or surgeons played.

Resident Training

Robot-assisted surgery as an evolving technology is also changing how surgical residents are educated. Furthermore, faculty surgeons need to gain their own experience while balancing training residents. 1 recent survey of program directors by Tom et al found that a 92% of programs have residents participating in robot-assisted surgery, while 68% offer formal curriculum; 44% track residents' robot-assisted experience; and about half (55%) recognize curriculum training completion. Another study also found wide variations "in requisite components, formal credentialing, and case tracking and role of simulation training". There is also no standardized approach on how to incorporate this training based on level of trainee. Overall, there is a need to adopt a standardized training curriculum and document resident competency.

Long-term Follow-up

Our work identified a lack of high quality evidence with adequate long-term follow-up and sufficient statistical power to properly assess clinical outcomes between the operative approaches for inguinal hernia repair and ventral hernia repairs. For hernia repairs, outcomes of interest need to include recurrent hernias beyond 1 year, long-term pain, and functional status. Only 1 small RCT was found for ventral hernia repair – none for inguinal hernia repair – and the 1 RCT only reported on 1 main outcome of interest. The data we found were too limited to provide conclusions in their regard.

Cholecystectomy Research Gaps

Our review focused on the use of robot-assisted surgery for benign, elective gallbladder disease. However, there is a need for future studies on cholecystectomy for non-benign pathology and emergent cases. As the robot-assisted technique is becoming more common, certain institutions are beginning to use it for cancer cases and non-elective surgeries, which are notably more complex. Given the differences in patient populations that experience these indications and the higher rates of complications for non-elective surgeries, the results from our study may not be generalizable to these populations. In fact, the robot-assisted approach may prove to be particularly advantageous for these more complex cases. The study of differences in cancer outcomes, and morbidity, for robot-assisted versus laparoscopic and open surgery is essential. As such, future research may consider expanding this review to examine different indications for cholecystectomy.

Inguinal Hernia and Ventral Hernia Repair Research Gaps

Specifically for hernia repairs, the robot-assisted approach may offer several technical advantages. For inguinal hernias, the potential for avoiding tacks or even the need for suturing mesh (sutureless mesh) may lead to less postoperative acute and chronic pain. For ventral hernia, the robot-assisted approach with improved suturing technique can also forego placement of tacks as well as possibly decrease recurrent hernia formation. Unfortunately, these technical details were not uniformly available across the studies in our review and outcomes were typically not reported by these factors. As such, it was not possible to determine their specific roles. Additionally, baseline pain was often not reported, perioperative quality of life and pain data were sparse, and long-term data on chronic pain and recurrence were rare. Standardized reporting in future work is needed in order to sufficiently assess pain outcomes, which needs to provide guidance on reporting technical aspects of the repair and requirements for clinical outcome assessment – specific time intervals, tools for assessing pain, and amount of pain medications taken.

Ergonomics for the Surgeon

An important issue that deserves study is the impact of the robot-assisted approach on the physical stress of the surgeon performing the operation. There is a high rate of musculoskeletal disorders attributed to poor ergonomics of laparoscopic surgery as well as the open approach. There are those that claim robot-assisted surgery ergonomics are superior, which translates into decreased physical stress and workload. However, there is also growing evidence that a prolonged time sitting at the robot-assisted console adds new physical challenges as well. 2 recent studies reported physical discomfort and symptoms or poor posture in over half of surgeons. Although data is sparse, it would be a valuable area for future research. While challenging to study, the outcomes would need to be comparative, long-term (5 year plus) and would require assessing detailed quality of life, assessment of chronic physical injuries, and longevity of operating over a career.

Future Innovation in Surgical Robotics

An overwhelming number of the studies in our review used the da Vinci system from Intuitive (only 1 study used the Senhance robot). The robot-assisted field is changing soon, as a number of new robot-assisted platforms are becoming available; there are 8 with FDA approval and more pending approval. These will bring with them potentially new advantages (*eg*, improved computer optics, machine learning, and automation) and possibly new challenges (*eg*, different technology with new learning curves, unknown impact on patient outcomes). Future research will be critical to assess the differences between these technologies. With these new market forces, there is anticipation for reduced cost as well.

Conflict of Interest

It is notable that reporting bias in robot-assisted surgery research has been identified. A recent study found that author payments from Intuitive were not declared in more than half (52%) of robot-assisted surgery research, and they reported more positive findings as compared to those that did declare their conflict of interest (COI) payments. There is a need to ensure full disclosure of COI with more accountability, and journals may want to adopt standardized processes to achieve better transparency.

Costs

Lastly, the lack of well-designed comparative studies also limits evaluations of cost. There is a need for standardized approaches to assess cost, which would apply to all 3 of these robot-assisted operations (*ie*, analytics approach, consistent definitions of cost, how upfront capital was accounted for, how to adjust for training staff, *etc*). Along these lines, formal cost-effectiveness studies that weigh the benefits and risks along with cost are needed.

Conclusions

Across 3 common general surgery procedures there is evidence that OR time is longer for the robot-assisted approach, and some signals that select intraoperative and postoperative complications are more favorable with the robot-assisted approach, based on the operation. Overall, the studies were heterogeneous in terms of patient characteristics and how the operations were performed and strong conclusions cannot be made. Cost is probably higher across these procedures, but the balance between the added expense and potential gains in effectiveness are unknown, until we adopt better, standardized methods of assessment.

ABBREVIATIONS TABLE

ASA	American Society of Anesthesiologists
BMI	Body mass index
CCI	Charlson comorbidity index
Chole	Cholecystectomy
COI	Conflict of interest
Comp	Complications
dVSSC	Da Vinci single-site cholecystectomy
EBDIT	Earnings before depreciation, interest and tax
EBL	Estimated blood loss
ED	Emergency Department
Elective	Elective surgery
FDA	Food and Drug Administration
F/U	Follow-up
GRADE	Grading of recommendations assessment, development and evaluation
IOC	Intraoperative cholangiogram
Lap	Laparoscopic approach
LC	Laparoscopic cholecystectomy
LOS	Length of stay
Mesh	Repair with mesh
Narc	Narcotic use
NIS	National Inpatient Sample
OR	Operating room or operating room time (where indicated)
Preop	Preoperative
Primary	Primary hernia repair
QOL	Quality of life
RAC	Robot-assisted cholecystectomy
RAS	Robot-assisted surgery
RC	Robotic cholecystectomy
RCT	Randomized controlled trial
Recur	Recurrence
Reop	Reoperation
SILC	Single incision laparoscopic cholecystectomy
ROBINS-I	Risk of bias in non-randomized studies- of interventions
Skin-to-skin	Operating time from skin incision to skin closure
SSI	Surgical site infection
SSO	Surgical site occurrence
TAPP	Transabdominal preperitoneal inguinal *hernia repair*
TEP	Totally extra-peritoneal inguinal hernia repair
Txf	Transfusion
TR	Total recurrences
USD	United States dollar

EVIDENCE REPORT

INTRODUCTION

Across the world, the adoption of robot-assisted surgery continues to increase, particularly for commonly performed general surgery procedures. In the US, the robot-assisted surgical platform was introduced in 1999 and by the end of 2017, over 3,000 robotic platforms were being used.[2] While this new technology is becoming widespread, several questions about the utility of robot-assisted surgery as compared to laparoscopic and open surgery persist. In particular, does the use of the robot translate to better or similar clinical outcomes for patients? Are operating room times and length of stay comparable or improved with use of robot as compared to laparoscopic or open techniques? These questions are critical to answer, both for patient safety and satisfaction, particularly in our current health care climate where hospitals and physicians must provide efficient care while maintaining the highest quality, all the while working to curtail costs.

Cholecystectomy and hernia repair are commonly performed general surgery procedures. Over 1 million cholecystectomies and 800,000 ventral and inguinal hernia repairs are completed annually in the US.[3,4] Robot-assisted approaches to these procedures are becoming more common and accepted.[5] Specifically, inguinal and ventral hernia repairs are the most rapidly growing procedures for the robot-assisted platform in general surgery. For example, a cohort study from the Michigan Surgical Quality Collaborative Database shows an increase in robot-assisted surgery general surgery procedures from 1.8% to 15.1% between 2012-2018.[6] In addition to multi-port laparoscopic and robot-assisted techniques, there has been a shift to single-port robot-assisted and laparoscopic approaches as well, which reduces the number of incisions for the patient.[7,8]

Further fueling this debate is the economics of the robotic platform. The robotic platform requires a significant upfront investment, an annual maintenance contract, and ongoing instrument purchases, not to mention staff and training costs, advertising, and infrastructure upgrade expenses. Weighing these costs relative to the potential benefits of the robot-assisted approach, such as reduced length of stay, complications, readmissions, or improved patient centered outcomes, is critical in our climate of needing to curtail rising health care costs.

In light of recent evidence in other surgical disciplines questioning the utility of the robotic platform, there is considerable need to understand the evidence surrounding the use of the robotic platform in general surgery. Few comprehensive systematic reviews addressing each of these procedures exist – specifically where the critical patient factors and technique differences are assessed.

In summary, common general surgery procedures make up a large volume of the annual operations performed in the US, and we are experiencing dramatic recent growth in the number of robot-assisted surgery cases within this field. Yet there is no consensus or guidelines on when to use this surgical approach, and such decisions are left up to individual practitioners. To help clinicians, patients, and policymakers decide between robot-assisted and other surgical approaches for cholecystectomy, inguinal or ventral hernia repairs, we were asked to conduct a systematic review of the literature.

METHODS

TOPIC DEVELOPMENT

This topic was developed in response to a nomination by Dr. Mark Wilson, National Director of Surgery, and Dr. William Gunnar, former National Director of Surgery. Key questions were then developed with input from the topic nominator, the ESP Coordinating Center, the review team, and the technical expert panel (TEP).

The Key Questions were:

KQ1A: What is the clinical effectiveness of robot-assisted surgery compared to conventional laparoscopic surgery for cholecystectomy?

KQ2A: What is the cost-effectiveness of robot-assisted surgery compared to conventional laparoscopic surgery for cholecystectomy?

KQ1B: What is the clinical effectiveness of robot-assisted surgery compared to conventional laparoscopic or open surgery for inguinal hernia repair?

KQ2B: What is the cost-effectiveness of robot-assisted surgery compared to conventional laparoscopic or open surgery for inguinal hernia repair?

KQ1C: What is the clinical effectiveness of robot-assisted surgery compared to conventional laparoscopic or open surgery for ventral hernia repair?

KQ2C: What is the cost-effectiveness of robot-assisted surgery compared to conventional laparoscopic or open surgery for ventral hernia repair?

Because the 3 surgical procedures were different, we constructed separate search strategies, inclusion and exclusion criteria for each procedure.

The review was registered in PROSPERO and is awaiting registration number.

SEARCH STRATEGY

We conducted separate searches for cholecystectomy, inguinal hernia, and ventral hernia. All searches included PubMed, Embase, and Cochrane (all databases) from 2010 to March 2020. For inguinal and ventral hernias, Medline was also searched from 2010 to 2020. The search used a broad set of common terms relating to "robotic surgical procedures" or “robotic-assisted” and “cost effectiveness”, and then the individual procedure-specific terms “inguinal hernia”, “ventral hernia” or “incisional hernia”, and “cholecystectomy”. Prior to 2010, robot-assisted procedures were not widely being performed and many surgeons were still in the so-called "learning curve". As such, our technical expert panel considered evidence from studies published prior to the year 2010 to be insufficiently relevant to modern practice. While we still anticipated finding studies assessing or including the robot-assisted surgery learning curve, this later search date will help lessen that occurrence. See Appendix A for complete search strategy.

STUDY SELECTION

Multiple team members working independently screened the titles of retrieved citations. For cholecystectomy, MMG and RS; for inguinal hernia repair, LY and MMG; for ventral hernia repair, LY, RS, MG, and MMG.

For titles deemed relevant by at least 1 person, abstracts were then screened independently in duplicate by multiple team members working in pairs. For cholecystectomy, RS and MMG; for inguinal hernia repair, LY, AT, and MMG; for ventral hernia repair, LY and MMG.

All disagreements were reconciled through group discussion. Full-text review was conducted in duplicate by 2 independent team members, with any disagreements resolved through discussion. For cholecystectomy, RS and MM; for inguinal hernia repair, LY and AT; for ventral hernia repair, LY and MMG.

Studies were included at either the abstract or the full-text level if they were randomized control trials or observational studies comparing robot-assisted surgery with either laparoscopic or open surgical approaches for any of the included surgical procedures. We also included publications of cost-effectiveness models that compared robot-assisted surgery with laparoscopic or open surgical approaches. We included all RCTs regardless of outcomes studied. We did not have sample size restrictions for cholecystectomy, but excluded studies with sample size <10 for inguinal and ventral hernia repairs. The cholecystectomy technique is very standard (with the exception of the number of ports). However, both hernia repair techniques are widely variable including factors such as mesh location, size of hernia, type of sutures, use of tacks, use of sutureless mesh, etcetera, and these continue to evolve. These factors were not consistently reported. As such, we made the decision that the small studies (<10 sample size) would have the potential for substantial unmeasured bias.

DATA ABSTRACTION

Data extraction was completed in duplicate. All discrepancies were resolved with full group discussion. We abstracted data on the following: study design, patient characteristics, sample size, intraoperative outcomes, postoperative outcomes, long-term functional outcomes and cancer outcomes, duration of follow-up, and data needed for the Cochrane Risk of Bias tool or Cochrane Risk Of Bias In Non-randomized Studies – of Interventions (ROBINS-I).

QUALITY ASSESSMENT

Randomized controlled trials were assessed for quality (risk of bias) with the Cochrane Risk of Bias tool.[9] This tool requires an assessment of whether a study is at high or low (or unknown) risk of bias in 7 domains: random sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessment, incomplete outcome data, selective outcome reporting, and other (See Appendix C for tool; Appendix E for table). We used the Risk Of Bias In Non-randomized Studies – of Interventions (ROBINS-I) for observational studies.[10] This tool requires an assessment of whether a study is at critical, serious, moderate, or low risk of bias (or no information) in 7 domains: 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, and bias in selection of the reported result (see Appendix D for tool; Appendix F for table).

The review team operationalized the 7 domains in the following manner:

Confounding factors

- Low: if patients have similar baseline characteristics, *OR* if significantly different, are propensity matched
- Serious: if baseline data is not explicitly stated

Selection bias

- Low: if consecutive series, *OR* if *likely* consecutive from a database study

Bias in measurement classification of interventions & bias due to deviation from intended interventions

- Low: by nature of the included studies

Bias due to missing data

- Studies with outcomes of 30 days or less were assumed to be 100% follow-up
- Moderate if loss to follow-up is unclear; serious if follow-up is reported, but low
- If studies exclude missing data in their study design then serious selection bias, but low for bias due to missing data
- If studies report an n-value in postoperative/long-term outcome tables that is consistent with their original n-value then that implies 100% follow-up
- Low: if no/minimal loss to follow-up

Bias in measurement of outcomes

- Split up outcomes by risk if there are differences
- OR times: likely low risk due to retrospective nature of most of these studies
- Pain: moderate risk due to patient subjectivity, lack of concealment, possible physician counseling, etc.

Bias in selection of the reported result

- Low: if authors report all available data, especially data with no significant differences
- Depends on the purpose and intended outcomes of the study, and whether other similar studies report omitted outcomes

DATA SYNTHESIS

Because the RCTs were too heterogeneous, we did not conduct a meta-analysis of trials. The observational studies were too clinically heterogeneous to support meta-analysis; hence, our synthesis is narrative.

We assessed robot-assisted and laparoscopic approach for cholecystectomy, as open cholecystectomy is typically performed for only cancer pathology. Therefore, robot-assisted cholecystectomy to open cholecystectomy is not clinically relevant. We assessed robot-assisted, laparoscopic, and open approaches for inguinal and ventral hernia repairs. Of note, cholecystectomy (for benign disease) and most inguinal hernias are performed as outpatient surgery.

Further, since there were limited RCTs, specific considerations for each of the 3 operations types were warranted, in order to account for a number of potential differences between study arms. Specifically, we needed to assess for within-study variations in patient factors and varying surgical techniques, which could confound effect differences in clinical outcomes. For example, if a robot-assisted surgery study arm had a higher number of bilateral hernias than the laparoscopic group, this in and of itself could potentially be responsible for longer operative times or higher rate of complications. Studies that performed matching (propensity matching) in our review accounted for a number of important variables but typically did not control for all relevant patient or technique factors (*ie*, extent of fascial closure, hernia size, *etc*).

Specifically, our research team made the following judgments to allow for the most optimal comparisons of the studies identified (which were mainly observational).

- For cholecystectomy, we present the data by grouping studies based on the number of surgical access ports used:
    - *robot single-port compared to laparoscopic single port or robot multi-port compared to laparoscopic multi-port;*
    - *robot single-port compared to laparoscopic multi-port;*
    - *robot compared to laparoscopic for those with unknown number of ports* (in terms of outcomes).

  We did not identify any study reporting robot multi-port to laparoscopic single-port.

- For inguinal hernia repair, we present the data by grouping studies where hernia laterality (unilateral or bilateral) was:
    - *known and at least <25% between comparative arms, or outcomes reported by laterality*;
    - *laterality not known.*

- For ventral hernia repair, we present the data by grouping studies that:
    - *attempted matching on patient, hernia, or technique factors;*
    - *matching not performed.*

RATING THE BODY OF EVIDENCE

We used the criteria of the Grading of Recommendations Assessment, Development and Evaluation (GRADE) working group.[11] GRADE assessing the certainty of the evidence based of the assessment of the following domains: risk of bias, imprecision, inconsistency, indirectness, and publication bias. This results in categories as follows:

High: We are very confident that the true effect lies close to that of the estimate of the effect.

Moderate: We are moderately confident in the effect estimate. The true effect is likely to be close to the estimate of the effect, but there is a possibility that it is substantially different.

Low: Our confidence in the effect estimate is limited. The true effect may be substantially different from the estimate of the effect.

Very low/Insufficient: We have very little confidence in the effect estimate. The true effect is likely to be substantially different from the estimate of effect.

PEER REVIEW

A draft version of the report was reviewed by technical experts and clinical leadership. Reviewer comments and our response are documented in Appendix B.

RESULTS

For cholecystectomy, we identified 887 potentially relevant citations, of which 169 were included at the abstract screening. From these, a total of 90 abstracts were excluded. Excluded abstracts were categorized as wrong comparison (n=54), systematic review (n=14), review/editorial (n=14), no outcome of interest (n=1), and other (n=7). This left 79 publications for full-text review, of which 32 were excluded for the following reasons: wrong comparison (n=4), no clinical data (n=3), no outcome of interest (n=4), review/editorial (n=8), other (n=2), and duplicate (n=11). A full list of excluded studies from the full-text review is included in Appendix H. A total of 47 publications were identified at full-text review as meeting initial inclusion criteria: RCT with cost and clinical data (n=1), RCTs with clinical data only (n=3), observational studies with cost data only (n=3), observational studies with clinical outcomes only (n=25), and observational studies with both clinical and cost data (n=15). Descriptions of included publications are available in the Evidence Table (Appendix G).

For inguinal hernia repair, we identified 3,319 potentially relevant citations and 9 publications recommended by experts. From these, 185 were included for abstract screening. A total of 143 abstracts were excluded, categorized as wrong comparison (n=129), no outcome of interest (n=1), other (n=6), systematic review (n=3), review (n=1), and duplicate (n=3). This left 42 publications for full-text review, of which 19 were excluded for the following reasons: wrong comparison (n=2), no outcome of interest (n=6), no clinical data (n=3), procedure (n=1), systematic review (n=1), review/editorial (n=2), duplicate (n=3), and unavailable (n=1). A full list of excluded studies from the full-text review is included in Appendix H. A total of 23 publications were identified at full-text review as meeting initial inclusion criteria: RCT with clinical and cost data (n=1), observational studies with clinical outcomes only (n=18), and observational studies with both clinical and cost data (n=4). Eleven studies had known hernia laterality that were similar distribution between study arms (<25% difference in laterality). While 6 studies with known laterality had >25% difference between comparison groups, for the other 6 studies, laterality was unknown or not reported (between the comparative arms). Descriptions of included publications are available in the Evidence Table (Appendix G).

For ventral hernia repair, we identified 3,458 potentially relevant citations and 5 publications recommended by experts. From these, 369 were included for abstract screening. A total of 321 abstracts were excluded, categorized as wrong comparison (n=306), review/editorial (n=8), no outcome of interest (n=8), systematic review (n=1), and duplicate (n=3). This left 48 publications for full-text review, of which 26 were excluded for the following reasons: case series with sample less than 10 (n=2), comparison (n=6), no outcome of interest (n=7), sample size less than 10 in each arm (n=2), review/editorial (n=1), systematic review (n=1), duplicate (n=6), and unavailable (n=1). A full list of excluded studies from the full-text review is included in Appendix H. A total of 22 publications were identified at full-text review as meeting initial inclusion criteria: RCT with clinical data only (n=1), observational study with cost data only (n=1), observational studies with clinical data only (n=15), and observational studies with both clinical and cost data (n=5). 7 of the observational studies reported matched data and 14 had unmatched data. Descriptions of included publications are available in the Evidence Table (Appendix G).

THE RISK OF BIAS OF STUDIES

For cholecystectomy, there were 4 RCTs and 40 observational studies. The RCTs in general were assessed to have an overall low risk of bias. Overall, the majority of the observational studies had high to moderate risk of bias, except for those with propensity matching (n=4).

For inguinal hernia repair, 1 RCT and 22 observational studies met inclusion criteria, including 6 abstracts. The RCT was assessed to have an overall moderate risk of bias due to the single-blinded design, unclear allocation concealment and blinding of outcome assessment, and potential for author bias due to the significant funding to multiple authors by the robot manufacturer. Overall, the majority of the observational studies had a high risk of confounding bias, as only 5 studies were propensity matched. Large differences (>25%) in or lack of reporting of the proportion of unilateral to bilateral inguinal hernia repairs also introduced confounding bias in 10 observational studies. Selection bias for the majority of studies was low; however, 8 studies were judged to have greater risk of bias due to study-specific patient exclusion criteria. Several papers also had author disclosures due to involvement with Intuitive Surgical Inc. Finally, we identified 1 study that conducted a random sample from a web-based research panel and was subject to numerous methodological limitations due to low response rate and high recall bias.[12]

For ventral hernia repair, 1 RCT and 20 observational studies met inclusion criteria. The RCT was a conference abstract of a small sample of patients and was judged to have an overall high risk of bias due to lack of allocation concealment, blinding of patients and personnel, blinding of outcome assessment, selective reporting, and use of self-reported outcomes, such as quality of life. The majority of the observational studies had a high risk of confounding bias, as only 8 studies were propensity matched, and of the matched studies, there was variation on which variables were being matched (*eg,* patient characteristics vs hernia size). Selection bias was overall low.

For all procedures, bias in the measurement classification of interventions, bias due to deviation from intended interventions, and bias in selection of the reported result were generally low. Bias due to missing data was overall low, as most studies only reported short-term (≤ 30 day) outcomes, which were presumed to have minimal loss to follow-up. Studies with long-term outcomes had a higher risk of bias due to missing data if follow-up rates were low 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 due to the subjectivity of these measurements, while objective assessments of pain, such as narcotic use, had a low risk of bias. Other outcomes, such as length of stay, complications, and OR time, had a low risk of bias.

Figure 1A. Literature Flow Chart

CHOLESCYSTECTOMY

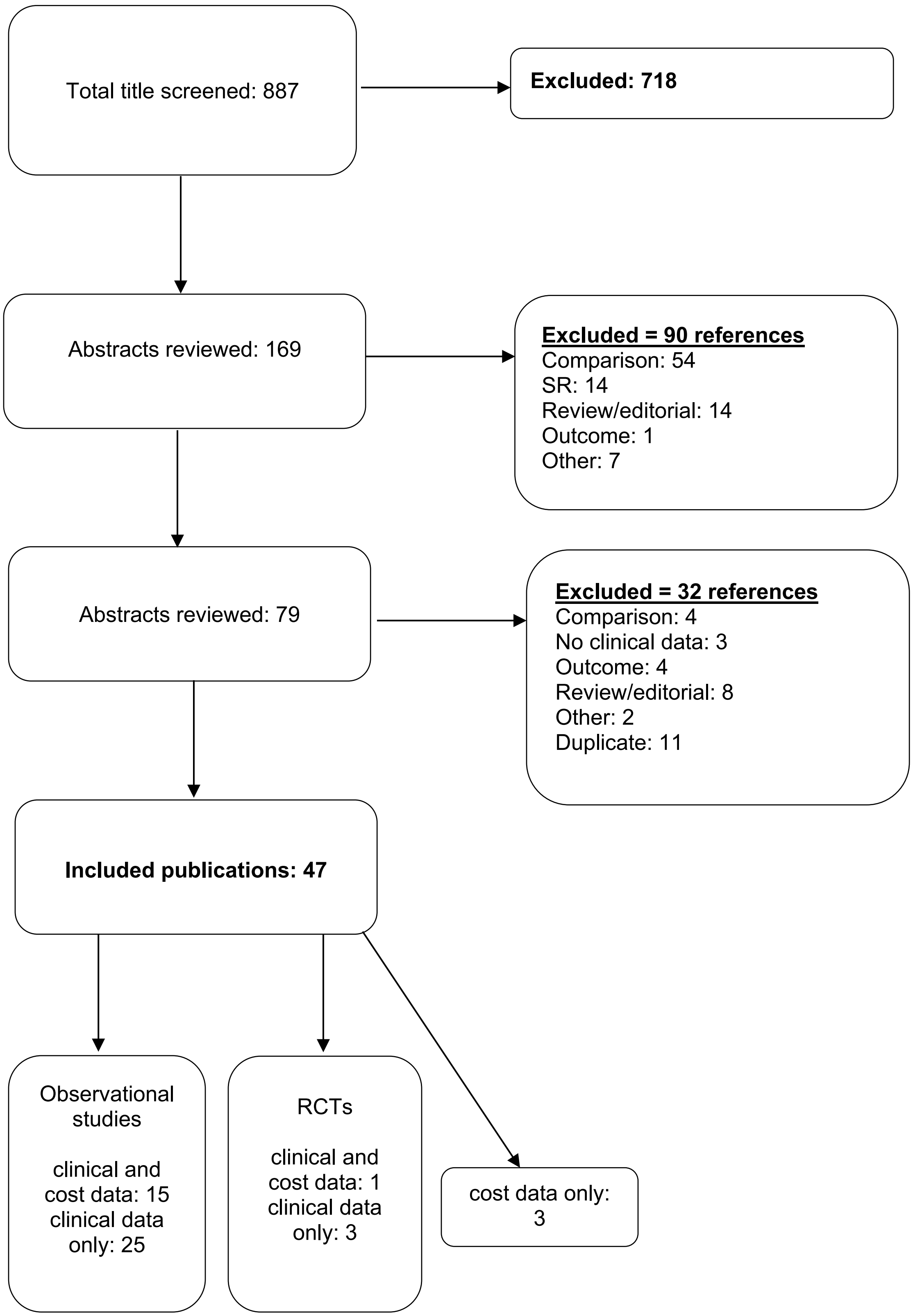


Figure 1B. Literature Flow Chart

INGUINAL HERNIA REPAIR

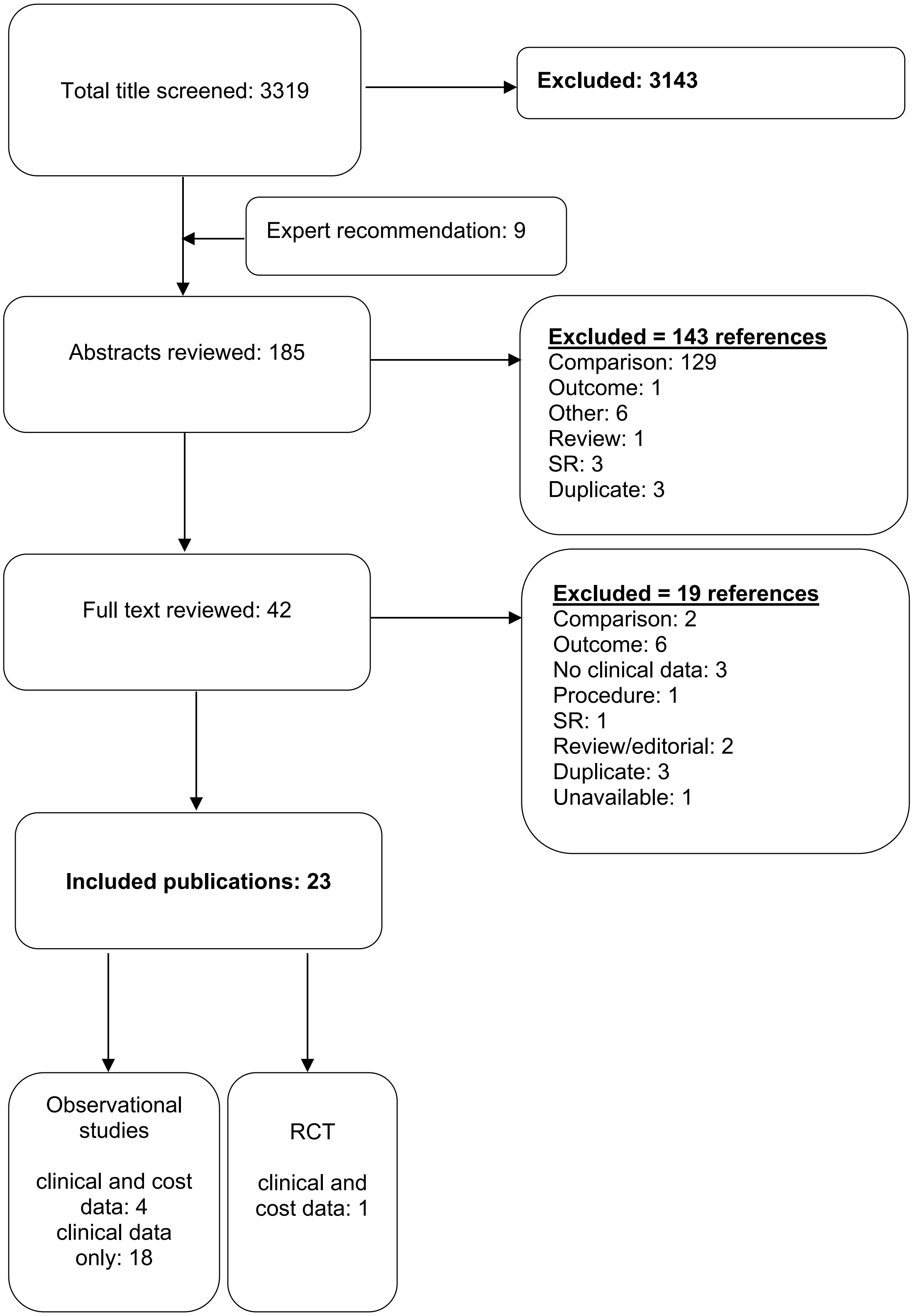
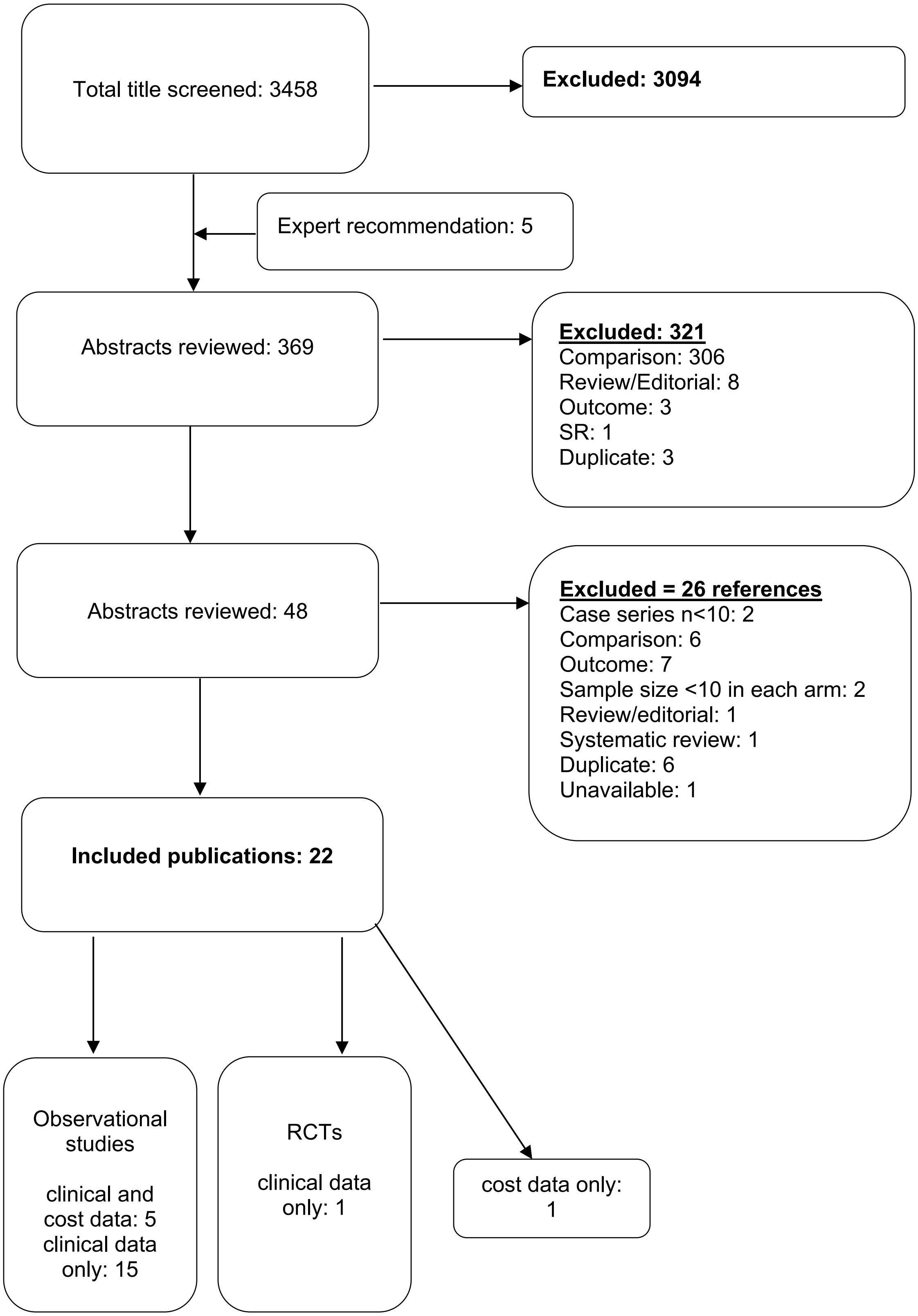


Figure 1C. Literature Flow Chart

VENTRAL HERNIA REPAIR

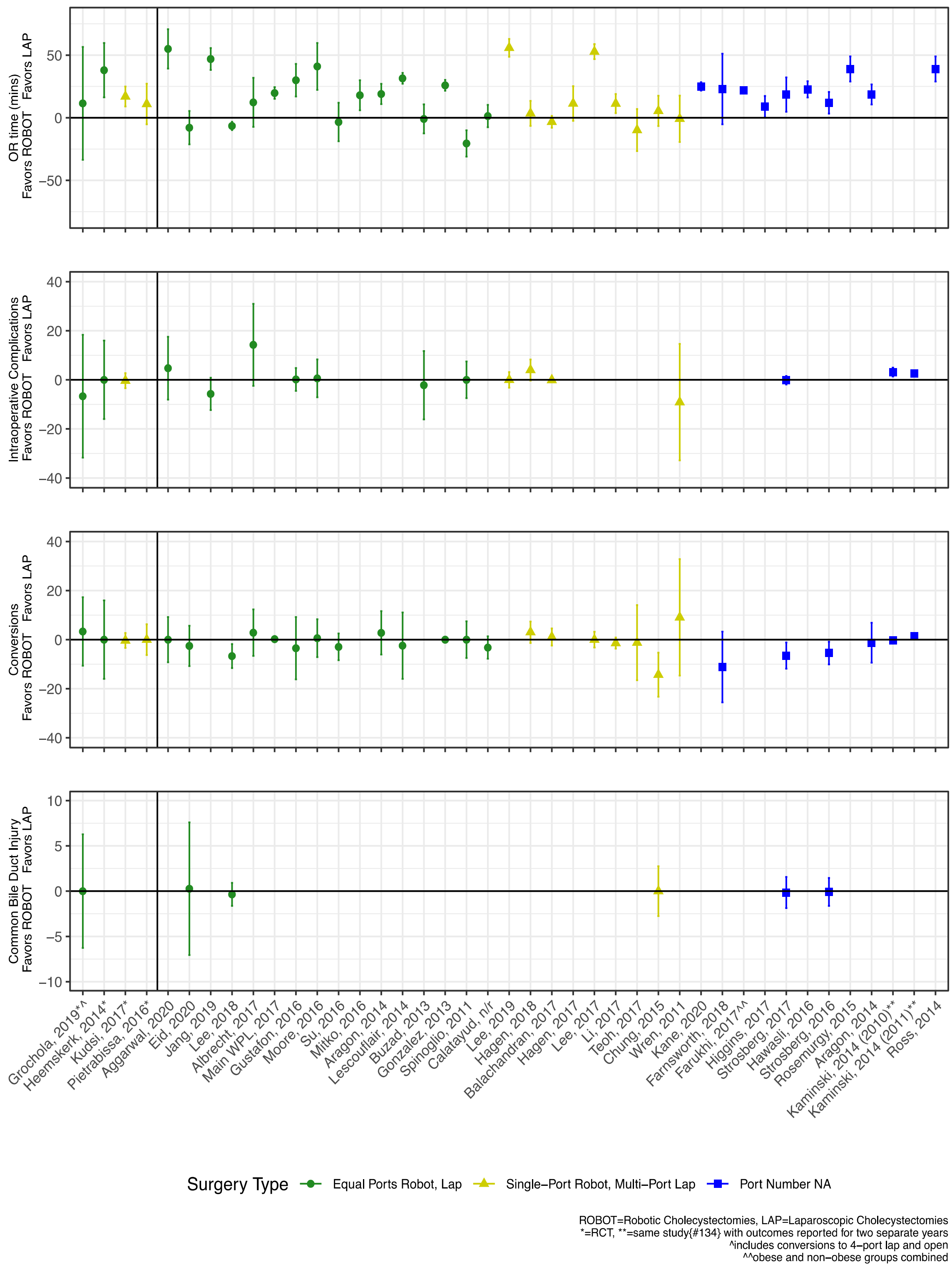


KEY QUESTION 1A – CHOLECYSTECTOMY: What is the clinical effectiveness of robot-assisted surgery compared to conventional laparoscopic surgery for cholecystectomy?

We identified 44 publications that met the inclusion criteria; 4 studies were randomized trials,[13-16] and the remaining studies were observational. 7 studies compared multi-port robot-assisted cholecystectomy with multi-port laparoscopic cholecystectomy,[14,17-22] including 1 RCT[14]; 12 compared single-port robot-assisted cholecystectomy with multi-port laparoscopic cholecystectomy,[15,16,23-32] including 2 RCTs[15,16]; and 11 compared single-port robot-assisted cholecystectomy with single-port laparoscopic cholecystectomy,[33-43] including 1 RCT.[13] 1 study compared 3 arms: single-port robot-assisted cholecystectomy, multi-port robot-assisted cholecystectomy, and single-port laparoscopic cholecystectomy.[44] Thirteen studies either grouped all (single and multi-port) robot-assisted and laparoscopic cholecystectomies in separate groups or did not specify if the robot and laparoscopic arms were single-port, multi-port, or both.[45-57] The studies varied in size from 20 to 735,537 patients.

Figure 2 presents graphically the results for 4 intraoperative outcomes: operating room (OR) time, complications, conversion to open cholecystectomy (or conversion from robot-assisted to laparoscopic cholecystectomy), and common bile duct injury. In the 4 RCTs, OR time was consistently longer for robot-assisted cholecystectomy procedures, although these differences were only statistically significant in 2 studies (one compared single-port robot-assisted cholecystectomy to single-port laparoscopic cholecystectomy[15] and the other multi-port robot-assisted cholecystectomy to multi-port laparoscopic cholecystectomy).[14] From the observational studies, robot-assisted cholecystectomy took longer to perform in the great majority of studies with most of these differences being statistically significant. Of the studies that demonstrated a shorter OR time in the robot cohort, only 2 were statistically significant, and they compared single-port robot-assisted cholecystectomy and single-port laparoscopic cholecystectomy.[37,41] For the outcomes of intraoperative complications, bile duct injury as its own outcome, or conversion rates, differences between robot-assisted cholecystectomy and comparison procedures were minimal to none, both in the RCTs and in the observational studies.

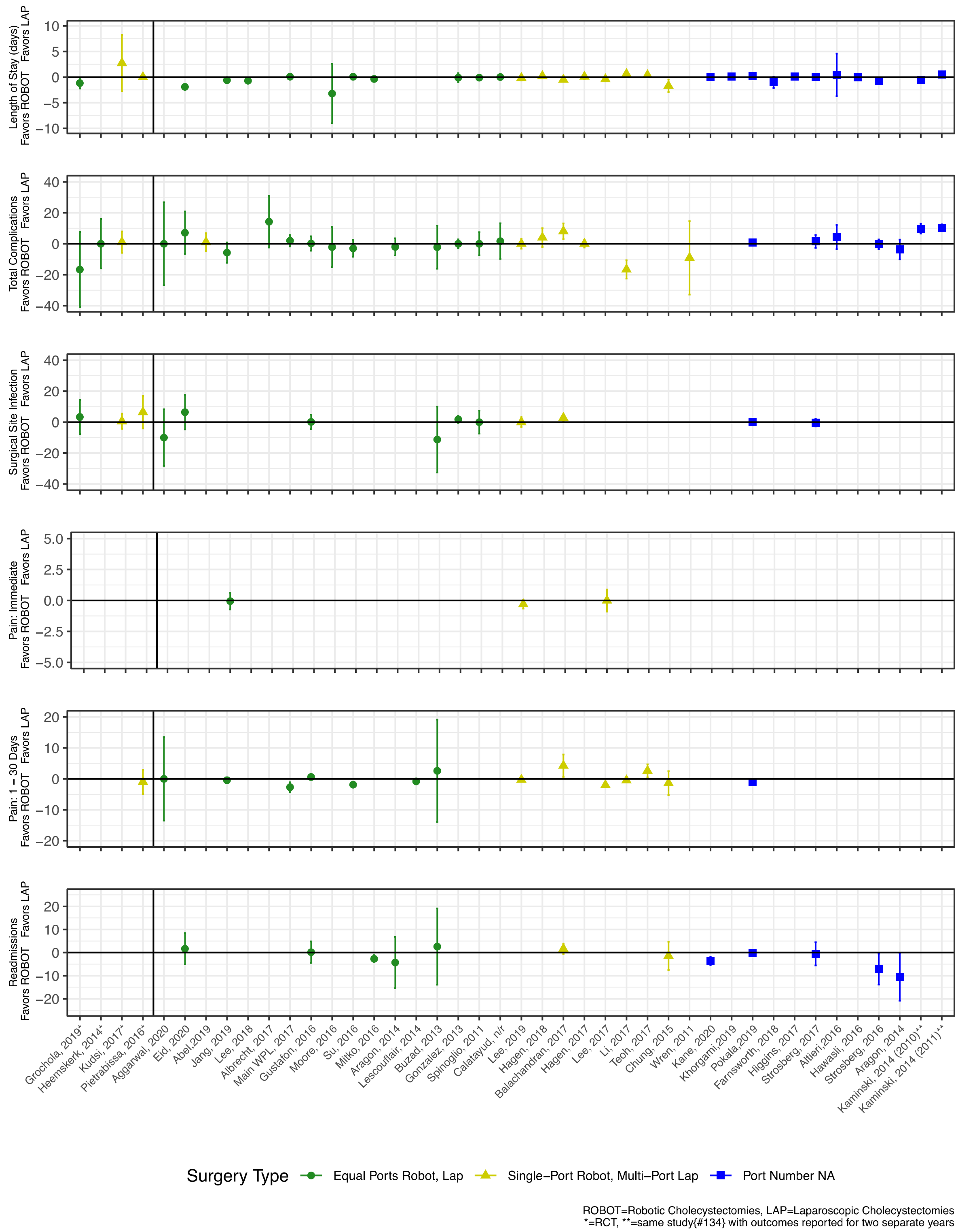
Figure 2. Cholecystectomy Intraoperative Outcomes



Graphed is the point estimate and 95% confidence intervals for the difference in the indicated outcome between robot-assisted cholecystectomy and laparoscopic approach. RCTs are listed in the left-hand side, while observational studies are listed on the right-hand side.

Figure 3 presents graphically the results of 6 short-term outcomes: LOS, all postoperative complications, surgical site infections, pain immediately following surgery, pain 1-30 days, and readmission rate. 3 out of 4 RCTs[13,15,16] reported on LOS, and this was significantly shorter in 1 study comparing the single-port robot-assisted cholecystectomy patients with single-port laparoscopic cholecystectomy patients.[13] In the other 2 RCTs, both of which compared single-port robot-assisted surgery to multi-port laparoscopic surgery, there was no significant difference in LOS.[15,16] In general, patients across all the RCTs and observational studies were discharged within 1 to 2 days without a suggestive pattern favoring any particular procedure. There were no significant differences in total complications or surgical site infections between procedures, and most point estimates were on or extremely close to the null value of no difference. There was somewhat more variation in point estimates of differences in the 2 pain outcomes, but no clear pattern favoring 1 procedure over another. Twelve observational studies reported readmissions, and 4 of these studies demonstrated a significantly higher readmission rate in the laparoscopic surgery patients.[20,44,54,57] Of those 4 studies, 1 had compared single-port robot-assisted cholecystectomy, multi-port robot-assisted cholecystectomy, and single-port laparoscopic cholecystectomy.[44]

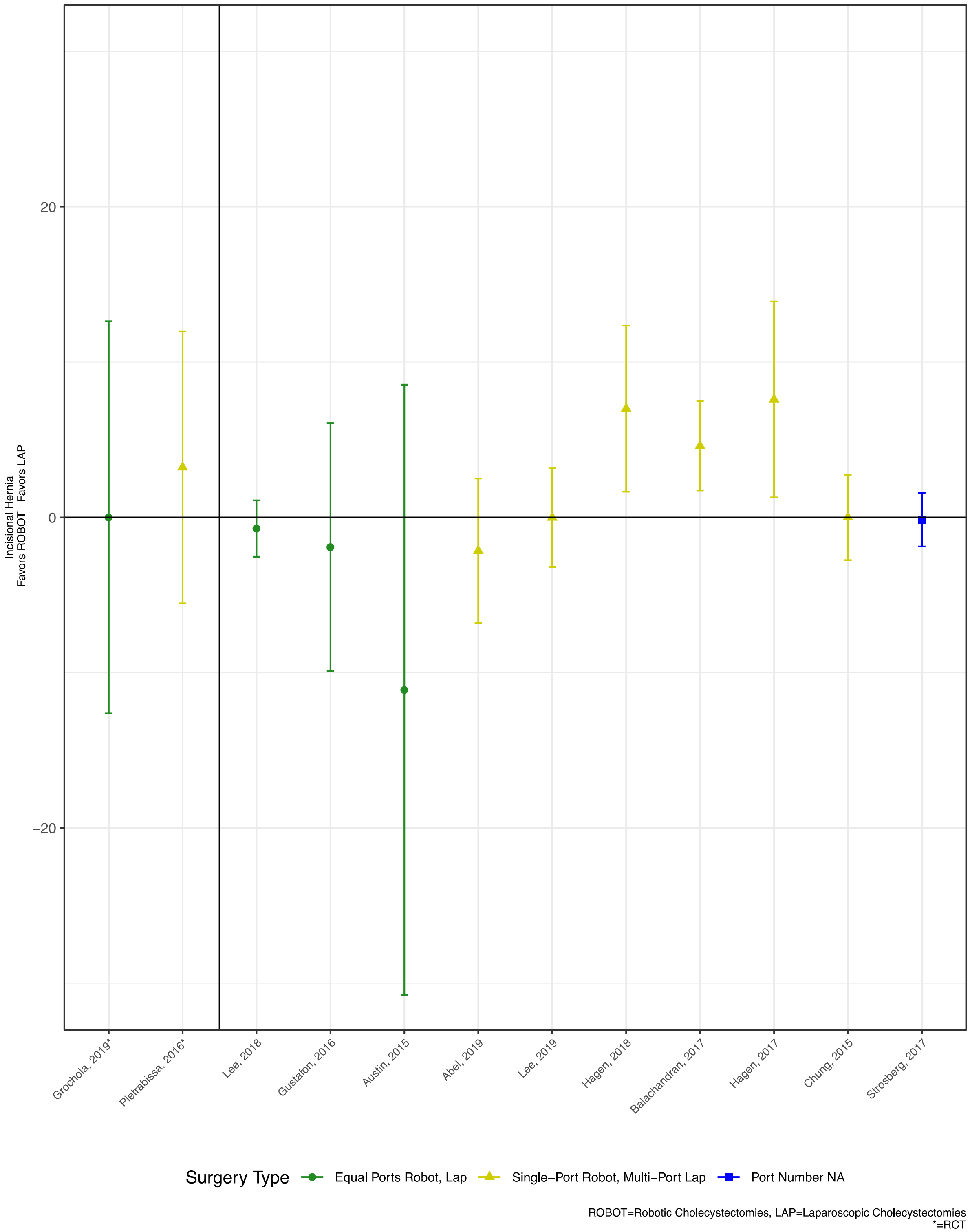
Figure 3. Cholecystectomy Short-term Outcomes



Graphed is the point estimate and 95% confidence intervals for the difference in the indicated outcome between robot-assisted cholecystectomy and laparoscopic approach. RCTs are listed in the left-hand side, while observational studies are listed on the right-hand side.

Figure 4 presents graphically the results of the only long-term outcome, incisional hernia rates. This outcome is less frequently reported than the short-term outcomes and is included in only 2 RCTs[13,16] and 10 observational studies.[23-25,27,30,32,36,39,41,51] The 2 RCTs[13,16] reported no statistically significant differences, but the 95% confidence intervals are very wide, and clinically important differences cannot be excluded. 3 observational studies[23,25,30] found higher incisional hernia rates in the single-port robot-assisted cholecystectomy patients compared to the multi-port laparoscopic cholecystectomy patients. The point estimate of effect for these 3 observational studies is within the 95% confidence interval of the 1 RCT of this comparison,[16] and in fact quite close to the RCT point estimate of effect. We interpret these findings as a possible signal that this long-term outcome may be worse in single-port robot-assisted cholecystectomy than multi-port laparoscopic cholecystectomy. In the remainder of the studies that reported on incisional hernia formation, there was no significant difference between robot-assisted cholecystectomy and laparoscopic cholecystectomy cohorts; 4 out of 6 of those studies compared single-port robot-assisted cholecystectomy to single-port laparoscopic cholecystectomy.

Figure 4. Cholecystectomy Long-term Outcomes



Graphed is the point estimate and 95% confidence intervals for the difference in the indicated outcome between robot-assisted cholecystectomy and laparoscopic approach. RCTs are listed in the left-hand side, while observational studies are listed on the right-hand side.

Summary of Findings

In general, OR time was longer in patients treated with robot-assisted cholecystectomy compared to laparoscopic cholecystectomy. While not always statistically significant, data are consistent across RCTs and observational studies, and also consistent with differences in OR time seen between other robot-assisted procedures and their laparoscopic or open counterparts. There was no evidence of differences in total intraoperative complications in total intra-operative complications or conversions, and most studies had point estimates close to the null value. Only 5 studies reported common bile duct injuries, and there was no evidence of differences between robot-assisted cholecystectomy and laparoscopic cholecystectomy. There was no evidence across most studies of differences in LOS, post-operative complications, or SSI. Pain was reportedly inconsistently among the studies and there was no evidence favoring robot-assisted or laparoscopic surgery. The lack of difference in outcomes between techniques could in part be related to patient selection and the type of gallbladder pathology for which each technique was used. Additionally, studies capturing surgeons' learning curve of the robot-assisted platform could factor in as well. The rate of incisional hernia may be higher in single-port robot-assisted cholecystectomy as compared to multi-port laparoscopic, a

All studies that demonstrated a statistically significant difference in incisional hernia rate compared single-port robot-assisted cholecystectomy to multi-port laparoscopic cholecystectomy. There was also no evidence of differences in the rate of incisional hernia rates for single-port robot-assisted and single-port laparoscopic cholecystectomy. This may be because the single-port approach with robot-assisted cholecystectomy or laparoscopic cholecystectomy involves a larger incision and confers a higher risk for developing an incisional hernia.

Certainty of Evidence for Key Question 1A

We judged the certainty of evidence for most outcomes as being moderate, with evidence from RCTs and from observational studies mainly in agreement on the direction of effect. We judged the evidence for most outcomes as imprecise, leading to a reduction in the certainty of evidence (from high to moderate). OR time outcomes for robot-assisted compared to laparoscopic cholecystectomy was deemed moderate because of imprecision. We judged the results for intraoperative complications as moderate due to some imprecision, and common bile duct injury was considered low because of imprecision and sparsity of data. We judged the certainty of evidence for conversion rate between robot-assisted cholecystectomy and laparoscopic cholecystectomy as high, based on the RCT data. We judged LOS as imprecise but moderate, since 3RCTs reported this result. All postoperative complications and surgical site infection as moderate certainty of evidence due to imprecision. We judged the certainty of evidence for readmission outcome between robot-assisted cholecystectomy and laparoscopic cholecystectomy as low. We judged the certainty of evidence for pain as low due to inconsistent and imprecise results. Certainty of evidence for postoperative incisional hernia formation between robot-assisted cholecystectomy and laparoscopic cholecystectomy was deemed low due to inconsistency among the comparison groups and imprecision.

Table 1. Certainty of Evidence for Cholecystectomy Studies

Outcome	Study Limitations	Consistency	Directness	Precision	Certainty of Evidence
Intra-operative					
OR Time Robot > Laparoscopic	RCT: Low Observational studies: High	Consistent	Direct	Imprecise	Moderate
Complications Robot = Laparoscopic	RCT: Low Observational studies: High	Consistent	Direct	Imprecise	Moderate
Common Bile Duct Injury Robot = Laparoscopic	RCT: Low Observational studies: Low	Consistent	Direct	Imprecise	Moderate
Conversions Robot = Laparoscopic	RCT: Low Observational studies: High	Consistent	Direct	Precise	High
Short-term Outcomes					
Length of Stay Robot = Laparoscopic	RCT: Low Observational studies: High	Consistent	Direct	Imprecise	Moderate
Complications (total) Robot = Laparoscopic	RCT: Low Observational studies: High	Consistent	Direct	Imprecise	Moderate
Surgical Site Infection Robot = Laparoscopic	RCT: Low Observational studies: High	Consistent	Direct	Imprecise	Moderate
Pain Robot = Laparoscopic	RCT: Low Observational studies: High	Inconsistent	Direct	Imprecise	Low
Readmissions Robot <Laparoscopic	Observational studies: High	Consistent	Direct	Imprecise	Low
Long-term Outcomes					
Incisional hernia Single port robot > multiport laparoscopic	RCTs: Low Observational studies: High	Inconsistent	Direct	Imprecise	Low

KEY QUESTION 2A – CHOLECYSTECTOMY: What is the cost-effectiveness of robot-assisted surgery compared to conventional laparoscopic surgery for cholecystectomy?

Eighteen studies looked at robot-assisted cholecystectomy versus laparoscopic and included some measure of cost. There was 1 RCT.[13] Of the remaining 17, the majority were retrospective, single institution, or single health system studies. There were 3 studies that used a national database[49,56,58] and 1 study performed a budget impact analysis using existing published data.[59] Studies were mixed with respect to procedures performed. Studies included a combination of traditional laparoscopic multi-port surgery, laparoscopic single-port surgery, robot-assisted multi-port surgery, and robot-assisted single-port surgery. Because most studies came from single institutions, sample sizes were generally small, with the majority of studies including fewer than 100 patients in the robot-assisted arm.

Overall, 16 of 18 studies reported at least 1 measure of cost higher for the robot-assisted surgery compared to the laparoscopic approach. The 1 RCT was a single institution study in Switzerland that evaluated 30 patients receiving single site robot-assisted surgery and compared them to 30 patients receiving single site laparoscopic surgery for elective cholecystectomy.[13] They found nearly a 50% higher cost for the robot driven by higher consumable costs, amortization, and overhead costs ("the cost of OR time").

Table 2. Evidence Table for Cholecystectomy Cost Studies

Author, Year, Number	Study Design, Number of Institutions	Comparison(s)	Number of surgeons	Sample Size	Source of cost data	Cost data	Misc. (Additional cost-pertinent outcomes and financial COI)
Bedeir 2016[60]	Retrospective, single institution	Robot-assisted single site vs traditional laparoscopic for elective outpatient cholecystectomy	1 (robot) 5 (lap)	46 robot 195 lap	"Cost data were obtained from financial department. Hospital cost in US dollars, not billed or hospital revenue. Cost divided into fixed and variable costs. **Only variable costs are included**. Fixed costs include salaries and hospital infrastructure. Fixed costs don't differ between. procedures."	Total median variable cost: 1319 (robot) vs 1737 (lap), p<0.001	Provide OR time for robot but not for lap One author had financial COI with Intuitive
Buzad 2013[33]	Retrospective, single institution	Robot-assisted single incision vs historical control of laparoscopic single incision cholecystectomies	1	20 robot 10 lap	"Cost based on instrument cost from preference cards; did not include purchase price or maintenance of robot. Sensitivity analysis performed for instrument costs: SILC estimates were average cost, based on number of cases, and a theoretical range for single port. Theoretical savings of no cholangiogram for robot was calculated."	Preference card cost for instruments = $1268 (robot) vs $1281 (lap); no p-value as these are just single values for the preference card **Excluded cost of using 5 "reusable" robotic instruments**	Operative times 84 vs 85 min, p=NS One author had financial COI with Intuitive
Farnsworth 2018[46]	Retrospective, single institution Abstract only	Robot-assisted vs laparoscopic acute care surgery cholecystectomy	2	14 robot 37 lap	"day of surgery until discharge"	Unadjusted OR costs: $3490 (robot) vs $2190 (lap), p<0.001 Adjusted analysis found robot was $980 more than lap BUT included OR time in analysis model	OR time 158 (robot) vs 132 (lap); P=NS Financial COI not discussed

Author, Year, Number	Study Design, Number of Institutions	Comparison(s)	Number of surgeons	Sample Size	Source of cost data	Cost data	Misc. (Additional cost-pertinent outcomes and financial COI)
Grochola 2019 [13]	RCT, single institution	Robot-assisted vs laparoscopic single site elective cholecystectomy	3	30 robot 30 lap	"Costs generated in the operating theatre include consumables needed for dVSSC and SILS (each patient), non-procedure-specific surgical and anaesthesiologic consumables (costs per min), amortization of equipment and staff salaries (costs per minute). Ward costs divided into medical and non-medical expenses as overhead per min.	Total cost (in Swiss Francs): 9743 (robot) vs 6900 (lap), p=0.001 Driven by: Higher consumables (2921 vs 882, p<0.001), amortization (932 vs 493, p=0.02), overhead costs in OR (1933 vs 1555, p=.017)	Total operative duration: 85.5 (robot) vs 74 (lap), p=NS Authors declared no conflicts
Gustafson, 2016[36]	Retrospective, single institution	Robot-assisted single-incision laparoscopic cholecystectomy (RSILC) vs traditional single incision laparoscopic cholecystectomy (TSILC)	1	38 robot 44 lap	"Operative costs were obtained from the hospital database"	Variable direct supply cost ($1,967 robot vs $1,969 lap, p=0.99) Variable direct labor cost ($1,234 robot vs $1,122 lap, p=0.34). Fixed direct cost:$8,961 robot vs $5,379 lap, p<0.0001 Mean service item charges (not defined):$14,594 robot vs $9,347 lap, p<0.0001). Total cost: $8,961.00 robot vs $5,379.00 lap	OR time 98 robot vs 68 lap, p<0.0001 Authors declared no conflicts

Author, Year, Number	Study Design, Number of Institutions	Comparison(s)	Number of surgeons	Sample Size	Source of cost data	Cost data	Misc. (Additional cost-pertinent outcomes and financial COI)
Hagen 2018[25]	Retrospective, single institution	Robot-assisted single site vs lap multi-port	Did not specify	99 robot 99 lap (matched analysis)	"Cost of the primary procedure was calculated including the capital investment and maintenance of robot with a flat fee per case as per hospital, instruments, and accessories per standardized OR procedure set, cost per OR-time of 17.3 USD per min in OR, and cost of hospitalization USD 627 for outpatients, and USD 1425 per day for inpatients as either previously established or per guidance of medical controlling department."	Total cost of index procedure $6158 (robot) vs $4288 (lap), p<0.0001 In addition: cost of follow-up surgery was $695 (robot) vs $0 (lap), p=0.02	Operative time: 97 min (robot) vs 94 min (lap), P=NS Incisional hernia requiring surgery rate: 7% (robot) vs 0% (lap), p=0.014 Author financial COI with Intuitive
Hawasli, 2016[55]	Retrospective, single institution	Robot-assisted cholecystectomy (14/26 with single incision RC, all included in 1 analysis) vs laparoscopic cholecystectomy (26/220 with single incision LC, all included in 1 analysis)	14	26 robot 220 lap	No discussion of cost methods	Mean direct cost: ($2,704.08 RC vs $1,712.50 LC, p<0.0001) Gross median margin w/ no difference ($1,726 LC vs $1,593 RC)	Mean case time RC: 121min vs LC: 98.4min, p<0.001 Mean OR time: RC: 86.6min vs LC: 63.9 min Financial COI not discussed
Higgins 2016[61]	Retrospective, single "health system"	Elective robot-assisted vs laparoscopic cholecystectomy	Did not specify	39 robot 343 lap	**See Footnote 1**	Total supply cost: $1699 (robot) vs $631 (lap), p<0.01	Case duration: 84 min (robotic) vs 76 min (lap), p=NS Authors had no financial ties to Intuitive

Author, Year, Number	Study Design, Number of Institutions	Comparison(s)	Number of surgeons	Sample Size	Source of cost data	Cost data	Misc. (Additional cost-pertinent outcomes and financial COI)
Kaminski 2014[58]	Retrospective, National Inpatient Sample (2010-2011)	Robot-assisted vs laparoscopic cholecystectomy for gallstone disease	Did not specify	524 + 1084 (robot, 2010/2011) 362,971 + 370,958 (lap, 2010/2011)	"NIS data include total charges for individual hospitalizations. HCUP provides cost-to-charge ratios, to convert charges to estimated hospital costs. Costs calculated as product of total charges and cost-to-charge ratio. Hospital costs reflect money expended for patient care (not physician expenses). Indirect (non-medical) costs were not available. NIS data don't allow calculating attributable costs."	Total costs: $21346 (robot) vs $13829 (lap) in 2010, p<0.05 $18224 (robot) vs $14181 (lap) in 2011, p<0.05	Authors declared no conflicts
Kane 2020[57]	Retrospective, Single Institution	Robot-assisted vs laparoscopic cholecystectomy	2	106 robot, 1060 lap	"Financial data were obtained from the Institutional Clinical Data Repository; Inflation estimates of the Center for Medicare and Medicaid Services Inpatient Prospective Payment System were used to adjust cost to 2017 US dollars to account for medical-specific inflation."	Hospital cost: $6611 (robot) vs $4930 (lap), p<0. 0001	Total OR time 185 min (robot) vs 160 min (lap), p<0.001 Authors declared no conflicts
Khorgami 2019[49]	Retrospective, National Inpatient Sample (2012-2014)	Robot-assisted vs laparoscopic cholecystectomy	Did not specify	1271 robot 69,402 lap	"Hospital total charges were converted to cost estimates using hospital specific cost-to-charge ratios provided by HCUP. Average total cost of hospitalization was compared for the LS and RAS cohorts. Difference between average costs of laparoscopic vs robotic were calculated for each surgical subgroup."	$10,944 (robot) vs $9618 (lap), "statistically significant", no p-value provided	Authors declared no conflicts

Author, Year, Number	Study Design, Number of Institutions	Comparison(s)	Number of surgeons	Sample Size	Source of cost data	Cost data	Misc. (Additional cost-pertinent outcomes and financial COI)
Lescouflair 2014[42]	Retrospective, single institution Abstract only	Robot-assisted single incision laparoscopic cholecystectomy (RSILC) vs single incision laparoscopic cholecystectomy (SILC)	1	41 RSILC 41 SILC	"Outcomes and cost were compared between the 2 groups." "Secondary outcomes include duration of narcotic use, time to independent performance of daily activities and cost."	Cost: $3,673 SILC vs $7,518 RSILC, p=0.056	OR time (min): RSILC 96.7 vs SILC 65.2 min, p<.00001 Conflicts not reported
Li, 2017[28]|	Retrospective, single institution	Single-site RC vs conventional LC (Number of ports not specified)	2	78 robot 367 lap	"Assessed data of total operation time, length of hospital stay, hospital charge, outpatient department (OPD) visits after discharge, and OPD service charges."	Results in New Taiwan Dollars: Average hospital charge: RC: 204,125 vs LC: 49,218, p=0.001 Average OPD charge: RC: 836.6 vs 509.6, p=0.001	OR time higher for RC (RC: 75.7min vs 64.37min,p=0.035) Authors declared no conflicts
Morris 2014[59]	Budget impact model for the UK NHS Abstract only	Robot-assisted vs laparoscopic cholecystectomy	NA	NA	"A model-based economic evaluation investigating cost of procedure accounting for operating staff, assistant time, theatre time, laparoscopic and robotic systems, instruments and LOS. Data from published sources."	Lap 2703 pounds vs robot 2877-15,253 pounds depending on service life and number of procedures per year	Conflicts not reported

Author, Year, Number	Study Design, Number of Institutions	Comparison(s)	Number of surgeons	Sample Size	Source of cost data	Cost data	Misc. (Additional cost-pertinent outcomes and financial COI)
Newman 2016[62]	Retrospective, single institution	Traditional lap vs single site lap vs single site robot-assisted	Did not specify	39 robot 11 single lap 50 traditional lap	**See Footnote 2**	"Direct variable surgeon cost": traditional lap $929 Single incision lap $1407 Robotic $2608 (all comparisons p<0.05)	Exact values not provided for OR time, ~ 65-75 for traditional, ~ 75-110 for single incision lap, ~ 90-105 for robot Authors declared no conflicts
Pokala 2019[56]	Retrospective, Vizient national database	Lap vs robot-assisted cholecystectomy for minor or moderate severity of illness	Did not specify	1,314 robot 53,028 lap	"Ratio of cost-to-charge (RCC) methodology is applied to estimate the cost of patient care along service lines"	Total cost: $8620 (robot) vs $6503 (lap), p<0.001	LOS: 3.27 (robot) vs 3.1 (lap), p<0.001 One author had financial COI with a robotic surgical company
Rosemurgy, 2014[50]	Retrospective, single institution	Laparoscopic vs Robot-assisted Cholecystectomy (did not specify how many incisions)	Did not specify	31 robot 201 lap	"Through the Decision Support Team, … Hospital Charges, Hospital Cost, Net Revenue, earnings before depreciation, interest, and taxes (EBDIT), and Net Income. Hospital Charges were the value requested for reimbursement. Hospital Cost was the value of money used to produce care described. Net Revenue defined as money received, regardless of cost of operation. EBDIT defined as Net Income before depreciation, interest, and income taxes. Net Income is value after Hospital Cost has been applied to Net	Charges RC $33,238.42 vs LC $25,055.85, p<0.01 Net revenue: RC $9,121.49 vs LC $6,512.61, p = 0.29 EBDIT: RC $6,196.07 vs LC $3,507.86, p=0.26 Net income: RC $5,848.59 vs LC $3,058.83, p=0.25	Operative duration: RC 140 vs Lap 93, p<0.01) No authors had financial ties to Intuitive

Author, Year, Number	Study Design, Number of Institutions	Comparison(s)	Number of surgeons	Sample Size	Source of cost data	Cost data	Misc. (Additional cost-pertinent outcomes and financial COI)
					Revenue. Hospital Cost data were subdivided into variable costs, fixed costs, supply costs, drug costs, equipment costs, and facility costs. Fixed costs were defined as expenses that were not dependent on the level of care provided by the hospital. Facility Costs included basic Hospital Costs which cannot be traced to individual patient care and are, rather, allocated to all patients adjusted for severity of intervention and illness.	Variable costs : RC \$1,714.30 vs LC \$1,449.54, p=0.022 Fixed costs: RC \$1,826.90 vs \$1,915.93, p=0.1665 Supply costs: RC \$594.74 vs LC \$636.65, p=0.4191 Drug costs: RC \$92.91 vs LC \$76.93, p=0.5575 Equipment costs RC \$336.96 vs LC \$345.14, p=0.5076 Facility costs: RC \$22.60 vs LC \$22.71, p=0.3099 Total costs: RC \$4,723.26 vs \$4,578.88, p=0.7265	
Strosberg, 2017[51]	Retrospective, single institution	Robot-assisted vs laparoscopic cholecystectomy (did not specify how many incisions)	1	97 lap (total) 140 robot (total) 35 lap (cost analysis)	"Cost data was obtained for each patient in the study group by our institution's financial division. Variables including total charges, total payments, total direct cost, total indirect cost, and total overall cost were collected. Direct cost defined as the sum of	Total charges: RC \$33,120 vs \$21,024, p<0.01 Total payments: RC \$7,478 vs \$5,887, p=0.34	Length of surgery longer for RC (74.5min vs 56min, p<0.01)

Author, Year, Number	Study Design, Number of Institutions	Comparison(s)	Number of surgeons	Sample Size	Source of cost data	Cost data	Misc. (Additional cost-pertinent outcomes and financial COI)
				68 robot (cost analysis) *Patients that had IOC, conversion to open or did not have a payment were excluded from cost analysis	operative and hospital cost. Revenue was calculated as total payments minus total overall cost. Exclusion for cost analysis included cases with uncaptured operative and in-hospital payments, inpatient procedures, and cases with intraoperative cholangiogram or conversion to open."	Total direct cost: RC $4,692 vs $2,983, p<0.01 Total indirect cost: RC ($4,243 vs $2,801, p<0.01 Total cost: RC $8,870 vs $5,771, p<0.01 Median revenue: RC -848 vs 186, p<0.01	

Footnote 1: "All data were obtained from the Surgical Profitability Compass Procedure Cost Manager System. Outcomes measured: LOS, case duration, and total supply cost. Total supply cost accounted for the cost of mesh. For robotic cases, total number and cost of robotic instruments were determined. Cost accounting for robotic instruments is determined by the purchase price of a particular instrument distributed equally among all the patients in whom the instrument was used."

Footnote 2: "We developed mechanics that could identify the portion of procedure cost under control of the surgeon. This was defined as direct variable surgeon cost (DVSC): surgical supply cost (drapes, gloves, etc); physician preference items; technology cost (per-use laparoscope cost, service contract amortized); and procedure time cost was variable cost of operating room use: 2.5 full-time equivalents per case minute. Proprietary robotic instruments are disposable after a pre-programmed number of uses, 5 or 10. Total cost of instrument divided by intended number of uses as each case cost: not corrected for actual number of uses."

Many of the studies had significant limitations, primarily related to the measurement of costs. Studies varied in terms of the detail provided as it relates to cost, with some providing no information at all. Others provided more specifics but only looked at 1 component of cost, such as disposable supply costs. Given the upfront cost of the robot, including the purchase price and ongoing maintenance costs, these cost assessments are incomplete. Studies also varied in their use of charges, payments, and costs, each of which will be more relevant to different parties. Charges, for example, are rarely paid by insurers and do not necessarily reflect the resources expended to care for the patient. Using cost-to-charge ratios to convert charges to costs is a blunt measure that is likely inaccurate, especially in surgery.[11] Even among studies that focused on hospital costs, whether they included staff costs or indirect costs varied from 1 study to the next and these details were often not explicitly mentioned. As a result, cost estimates varied markedly across studies from as low as $1400 to as high as $33K. No study commented on updating costs based on inflation nor did they reference any type of recognized methodology when reporting cost information (*eg*, Second Panel on Cost Effectiveness, CHEERS).

Summary of Findings

While there are a number of studies comparing robot-assisted versus laparoscopic surgery for cholecystectomy, all had significant limitations, primarily surrounding the cost methodology used (or lack of methodology). Nevertheless, there was an almost unanimous finding, including in randomized data, that the robot-assisted approach is more expensive than laparoscopic.

Certainty of Evidence for Key Question 2A

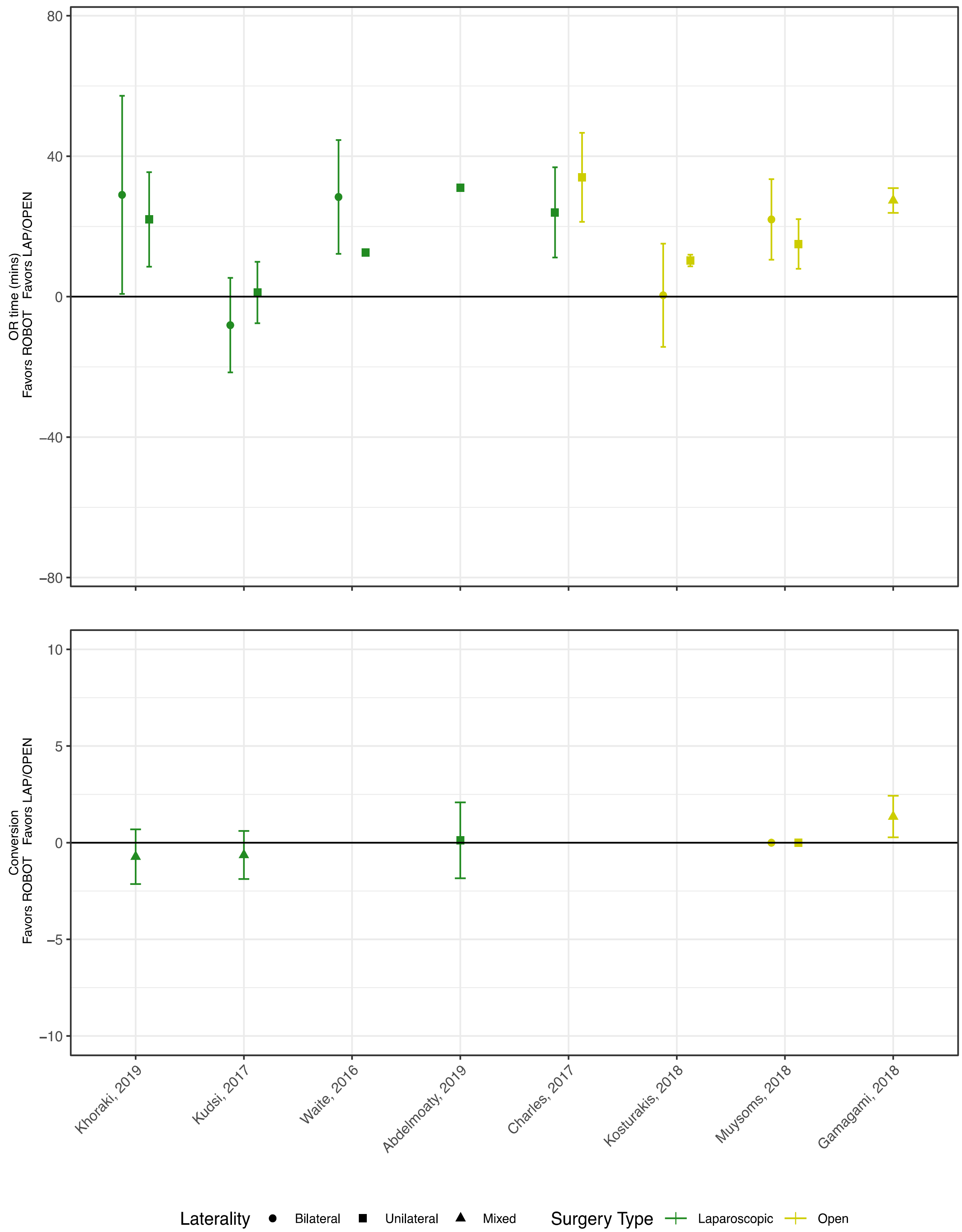
Despite wide heterogeneous methodologic approaches to assessing cost in these studies and differing definitions of cost, nearly all found that robot-assisted approach for cholecystectomy was more expensive than laparoscopic. This directness and consistency support that that we have moderate certainty that robot-assisted is more expensive than laparoscopic cholecystectomy. How much more expensive is not known with precision.

KEY QUESTION 1B – INGUINAL HERNIA SURGERY: What is the clinical effectiveness of robot-assisted surgery compared to conventional laparoscopic or open surgery for inguinal hernia repair?

We identified 23 publications that met inclusion criteria. There was 1 RCT, which was a US multi-institutional study of 102 patients assessing short-term outcomes between robot-assisted and laparoscopic unilateral inguinal hernia repair.[63] The remaining 22 studies were observational. Of these, 16 specified laterality in the patient demographics.[64-79] 4 studies reported on unilateral inguinal hernia only, [64,68,71,75] while 12 reported on both unilateral and bilateral.[65-67,69,70,72-74,76-79] The robot-assisted approach was compared to the laparoscopic approach in 18 studies.[12,64,65,68,70-83] Similarly, the open approach was compared to robot-assisted in 14 studies.[12,66-72,77,79,80,82-84] 8 studies included primary and recurrent hernias.[67,69,70,73-76,78] Of the remaining 14 studies, 5 reported only on primary hernias[68,71,79,80,84] and the other 9 did not specify.[12,64-66,72,77,81-83] Two studies were performed outside of the US.[72,73] Also, 3 studies reported outcomes from patients who were served at the Veterans Affairs hospital system.[67,68,70] 8 studies utilized prospectively maintained datasets.[64,68,,71,73,77,80,82,84] The studies varied in size from 55 to 75,981 patients. Propensity matching was performed in 5 studies.[12,66,69,77,83] Of note, 2 studies published by the same group utilized overlapping patient samples,[66,69] of which 1 study only examines the outcomes for the subgroup of patients who are obese.[66] Thus, only the study assessing the broader subset of patients is plotted in the subsequent figures.[69]

Intraoperative outcomes included OR time and rate of conversion from robot-assisted or laparoscopic surgery to open (Figure 5). Of the 8 studies included in this analysis, 5 compared robot versus laparoscopic approach, and 4 compared robot to open approach.[65,67-69,73-75,78] With 2 exceptions, all studies found that OR time was longer for the robot-assisted approach compared to either the laparoscopic approach or the open approach. One study reported similar increased OR time with unilateral laparoscopic robot-assisted inguinal hernia repair compared to robot-assisted laparoscopic surgery.[67] However, there was no evidence of differences between the 2 approaches for bilateral inguinal hernia repair. Another study assessed the learning curve of an experienced surgeon and found length of OR time decreased with experience and was not different at the end of the study.[74] There was no evidence of differences in conversions between robot-assisted and laparoscopic approaches.

Figure 5. Inguinal Hernia Intraoperative Outcomes



Graphed is the point estimate and 95% confidence intervals for the difference in the indicated outcome between robot-assisted inguinal hernia repair and either laparoscopic (green) or open (gold) approaches.

Four postoperative short-term (≤30 days) outcomes were assessed for inguinal hernia repair: LOS, surgical site infections (SSI), readmissions, and total complications (Figure 6). Of the 5 studies assessing outcomes for LOS,[65,69,75,77,78] 2 studies demonstrated significantly decreased inpatient LOS for robot-assisted inguinal hernia repair compared to open approach,[69,77] and 1 of these studies[77] demonstrated significantly decreased inpatient LOS for robot-assisted repair compared to laparoscopy as well. We elected to only graph the outpatient LOS in the corresponding figure, for which there was no difference among the 3 approaches, as this represents the more common disposition for this surgery. Two studies that looked at unilateral repairs did not show a difference between robot-assisted and laparoscopic approaches.[75,78] The final study reported outcomes for both unilateral and bilateral repairs, and they also found no difference in LOS for robot-assisted versus laparoscopic approach.[65]

Of the 7 studies assessing outcomes for SSI,[63,64,67-69,74,78] the RCT reported a trend to lower SSI rate when comparing robot-assisted to laparoscopic surgery,[63] and 2 studies reported a trend to lower SSI rate in robot-assisted surgery compared to open,[67,69] but none of these studies met statistical significance (Figure 6). In contrast, 2 studies reported a non-significant trend to higher SSI rate in robot-assisted surgery compared to laparoscopic and open surgery.[68,78] The 2 remaining studies did not report a significant difference in SSI rates between robot-assisted versus laparoscopic approaches.

Five studies assessed outcomes for readmission following inguinal hernia repair.[64,68,69,74,78] One study that compared all 3 approaches for unilateral hernias found that readmission rates were lower for robot-assisted as compared to either laparoscopic or open approaches.[68] The remaining 4 studies did not find a significant difference in readmission rates: 3 assessed robot versus laparoscopic repair (unilateral and a mix of laterality),[64,74,78] and 1 assessed robot versus open (for mix of laterality).[69]

Nine studies assessed outcomes for total complications.[63,64,67-69,71,73,74,78] Only 1 observational study found lower complication rates for the robot-assisted approach, which was seen in both the laparoscopic and open comparative arms.[71] Of note, this study looked at only unilateral hernia repair. The remaining 10 studies, including the RCT, did not demonstrate significant differences in complications by approach: 6 studies assessed robot-assisted compared to laparoscopic approach (4 of which were on unilateral and 2 were mixed laterality)[63,64,68,74,75,78] and 4 assessed robot-assisted to open repair (2 on unilateral hernias, 1 on bilateral hernias, and 3 on a mix of laterality[67-69,73]).

Figure 6. Inguinal Hernia Postoperative Short-term Outcomes

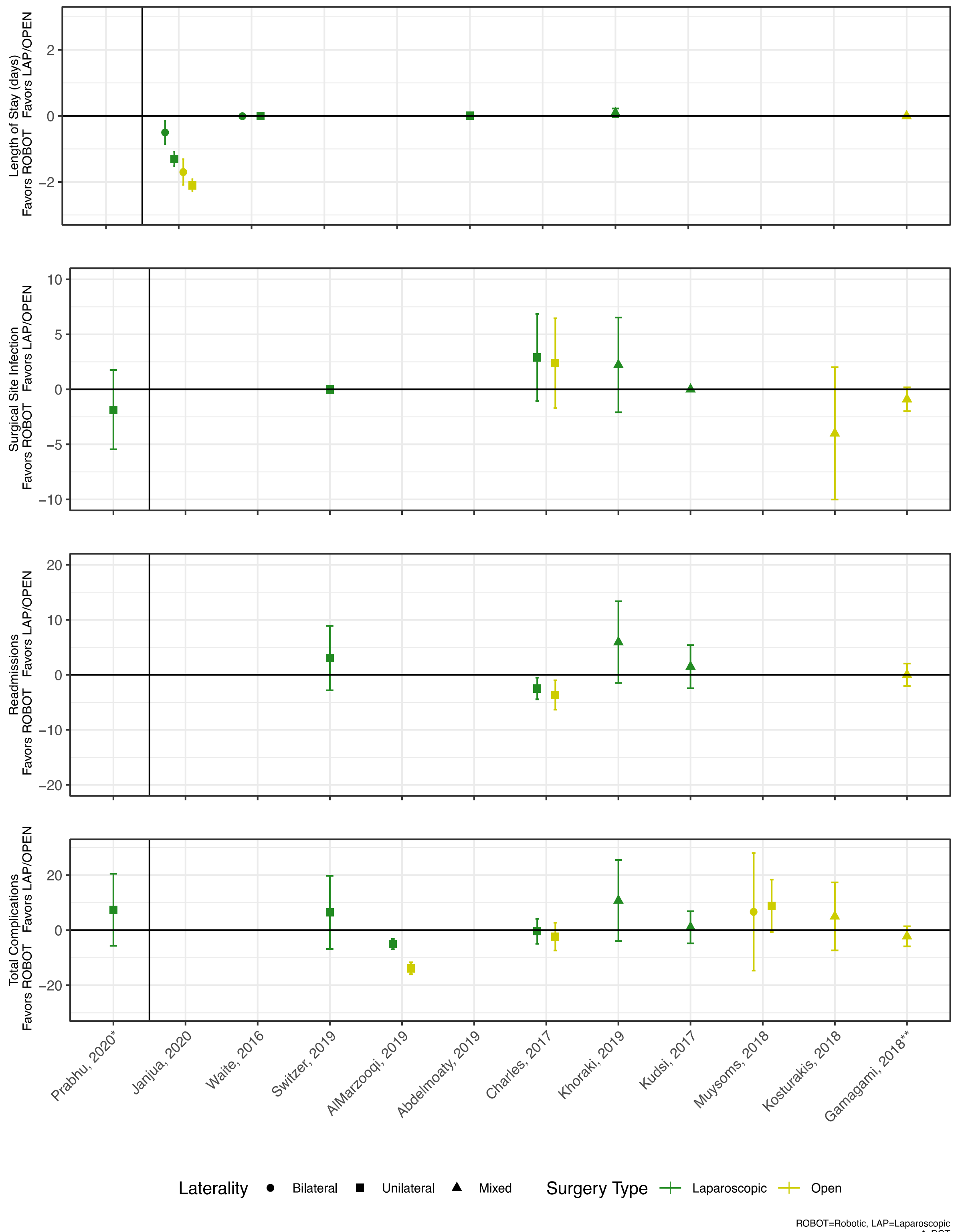
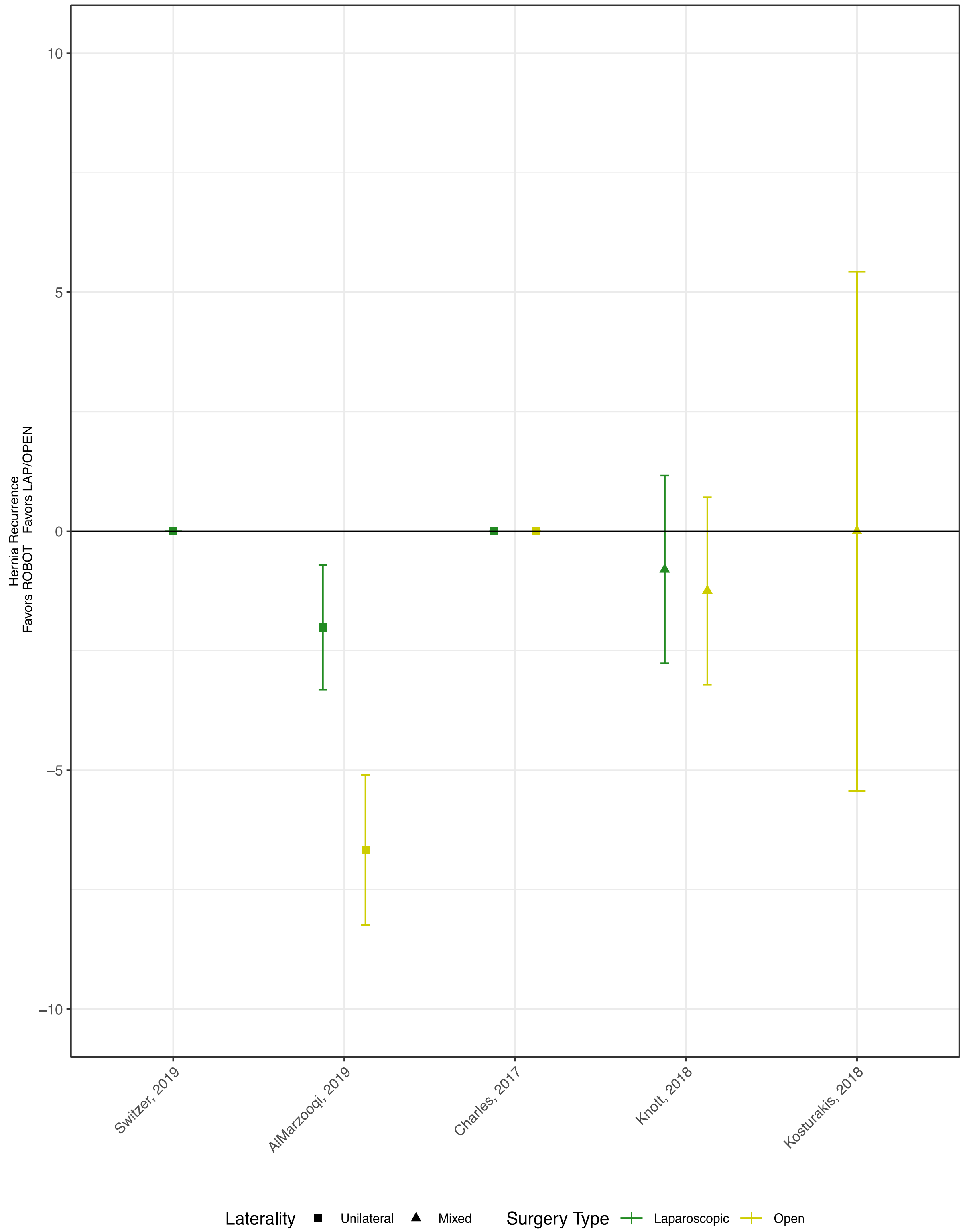


Figure 6 footnote: Only outpatient LOS was plotted for the LOS outcome.
Graphed is the point estimate and 95% confidence intervals for the difference in the indicated outcome between robot-assisted inguinal hernia repair and either laparoscopic (green) or open (gold) approaches.

For long-term outcomes, 5 studies assessed inguinal hernia recurrence (Figure 7).[64,67,68,71,80] One study demonstrated lower recurrence rate for the robot-assisted approach as compared to both laparoscopic and open repair (for unilateral hernia repair).[71] Two did not demonstrate a statistically significant difference that assessed both robot-assisted to laparoscopic and open comparative arms.[68,80] Two additional studies also didn't show differences in recurrence rates: 1 assessed robot-assisted to laparoscopic comparing unilateral hernia repairs,[64] and another study comparing a mix of hernia laterality for robot to open repair.[67]

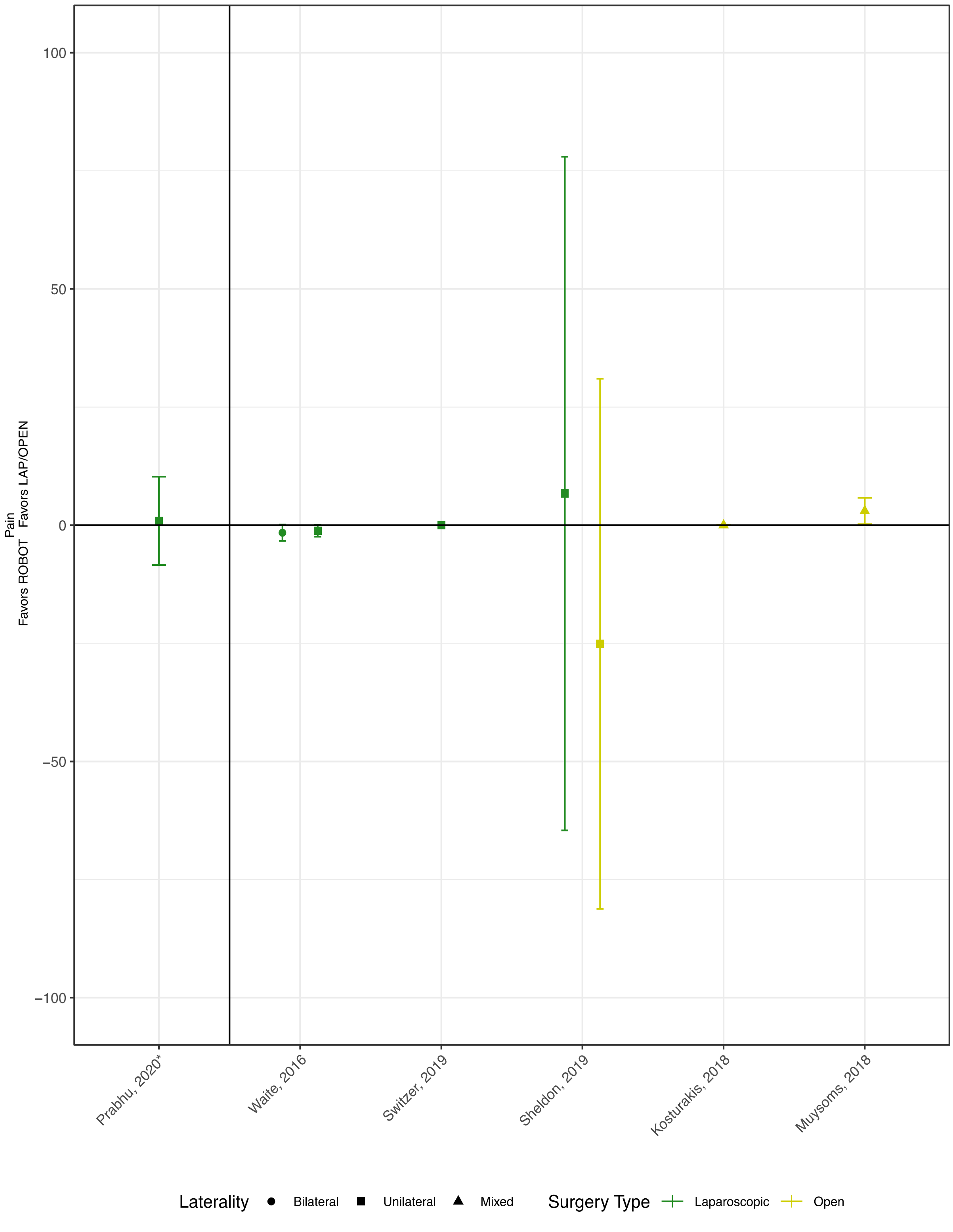
Figure 7. Inguinal Hernia Postoperative Long-term Outcomes



Graphed is the point estimate and 95% confidence intervals for the difference in the indicated outcome between robot-assisted inguinal hernia repair and either laparoscopic (green) or open (gold) approaches.

Six studies assessed postoperative pain following inguinal hernia repair (Figure 8).[63-65,67,73,79] The RCT did not show a significant difference in pain outcomes for robot-assisted compared to laparoscopic inguinal hernia repair.[63] One observational study reported worse pain for the robot-assisted approach as compared to open repair for a mix of hernia laterality.[73] The remaining observational studies did not demonstrate a significant difference in pain among robot-assisted, laparoscopic, and open inguinal hernia repair for unilateral, bilateral, and mixed laterality repairs.

Figure 8. Inguinal Hernia Postoperative Pain Outcomes



Graphed is the point estimate and 95% confidence intervals for the difference in the indicated outcome between robot-assisted inguinal hernia repair and either laparoscopic (green) or open (gold) approaches.

Summary of Findings

Operative room time was longer in patients treated with robot-assisted inguinal hernia repair compared to laparoscopic or open repair, particularly for unilateral hernia. There were no differences in conversions between robot-assisted and laparoscopic approaches. In terms of LOS, there may be a signal of a small benefit favoring the robot-assisted approach compared to open surgery for inpatient stays, but no difference for outpatient surgeries, which is the more common practice. There does not appear to be a signal of benefit with regard to SSI for the robot-assisted approach compared to laparoscopic or open surgery. There may be a small signal of benefit for lower readmissions with the robot-assisted approach for unilateral hernias. Regarding total short-term postoperative complications and hernia recurrences, there is minimal to no benefit of the robot-assisted approach for inguinal hernia repair compared to the laparoscopic or open approaches. Most studies demonstrated no difference among approaches when assessing postoperative pain.

Certainty of Evidence for Key Question 1B

Only 1 RCT was included in our analysis, for which there was greater certainty of evidence; however, it was judged as having moderate study limitation due to its single-blinded design with unclear allocation concealment and blinding of outcome assessment and potential for author bias. Due the observational nature of all remaining eligible studies, the study limitations were high and certainty of evidence was subsequently lower. We judged the certainty of evidence for the outcomes of longer OR time for robot-assisted inguinal hernia repair compared to laparoscopic and open inguinal hernia repair as low, primarily because data was imprecise. We judged the certainty of evidence that LOS for inpatient stays following robot-assisted surgery is shorter compared to open repair and no difference in outpatient LOS as moderate. Evidence that LOS for robot-assisted was not different compared to laparoscopic repair was determined to be moderate. We judged the certainty of evidence that SSI rates following robot-assisted surgery were not different as compared to laparoscopic and open repair as low due to inconsistency and imprecision of the data. We deemed certainty of evidence that readmissions following robot-assisted surgery were similar to the other 2 approaches as low based on inconsistency in the data. The evidence of no difference in major complications and recurrences among the surgical techniques was assessed as very low due to inconsistency and imprecision of the data. The certainty of evidence that there is no difference in postoperative pain among the 3 approaches was judged as low due to inconsistency and imprecision.

Table 3. Certainty of Evidence for Inguinal Hernia Repair Studies

Outcome	Study Limitations	Consistency	Directness	Precision	Certainty of Evidence
Intraoperative					
Operating Room Time Robot > Open/Laparoscopic	Observational studies: High	Consistent	Direct	Imprecise	Moderate
Postoperative Short-Term Outcomes					
Length of Stay Robot < Open (inpatient)	Observational studies: High	Consistent	Direct	Precise	Moderate
		Consistent	Direct	Precise	Moderate

Outcome	Study Limitations	Consistency	Directness	Precision	Certainty of Evidence
Robot = Open (outpatient) Robot = Laparoscopic		Consistent	Direct	Precise	Moderate
Surgical Site Infection Robot = Open/ Laparoscopic	RCT: Moderate Observational studies: High	Inconsistent	Direct	Imprecise	Low
Readmissions Robot = Open/ Laparoscopic	Observational studies: High	Consistent	Direct	Imprecise	Low
Total complications Robot = Open/ Laparoscopic	RCT: Moderate Observational studies: High	Inconsistent	Direct	Imprecise	Low
Postoperative Long-Term Outcomes					
Hernia Recurrence Robot = Open/ Laparoscopic	Observational studies: High	Consistent	Direct	Imprecise	Very Low
Pain Robot = Open/ Laparoscopic	RCT: Moderate Observational studies: High	Inconsistent	Direct	Imprecise	Low

KEY QUESTION 2B – INGUINAL HERNIA SURGERY: What is the cost-effectiveness of robot-assisted surgery compared to conventional laparoscopic or open surgery for inguinal hernia repair?

There were 5 studies that reported cost information for inguinal hernia repairs. There was 1 RCT.[63] Of the remaining 4 studies, 3 were single-institution retrospective reviews[65,68,78] and the last was a retrospective review of a national database.[77] The 1 randomized trial compared robot-assisted and laparoscopic transabdominal hernia repairs at 6 institutions in the United States. They limited inclusion to only surgeons who had performed at least 25 prior robot-assisted and laparoscopic procedures. With respect to cost, they found the robot-assisted approach had over twice the hospital cost of the laparoscopic approach ($3,258 vs $1,421). They did not include capital equipment costs in their analysis.

Three of the 4 remaining studies also found the cost of the robot-assisted approach to be higher than the cost of the laparoscopic approach. Details regarding what went into cost estimates were generally limited. One study did not mention any information aside from "financial data were obtained from the institutional Clinical Data Repository." The 1 study that did not find a cost difference excluded a large component of robot-assisted costs (purchase price of equipment and annual contract),[2] likely accounting for their null findings. None of the studies comment on how they accounted for staff/labor costs, which are the largest component of OR costs.[10] This point is important as all 4 that reported operative time found operative time to be longer in the robot-assisted arm compared to the comparison arms. None of the studies reference a recognized methodology when reporting cost information (*eg*, Second Panel on Cost Effectiveness, CHEERS).

Table 4. Evidence Table for Inguinal Hernia Cost Studies

Author, Year, Number	Study Design, Number of Institutions	Comparison(s)	Number of surgeons	Sample Size	Source of cost data	Cost data	Misc. outcomes
Charles, 2017[68]	Retrospective review, single institution	Robot-assisted vs lap vs open primary unilateral inguinal hernias	10	69 robot 241 lap 191 open	"Financial data were obtained from the institutional Clinical Data Repository."	Hospital cost: Robot $7162, lap $4527, open $4264 (p<0.001)	OR time longer for robotic surgery (105 min robot, 81 min lap, 71 min open; p<0.001) No difference discharge home same day
Janjua 2020[77]	Retrospective, HCUP-State Inpatient Databases & AHA data from 8 states (2009-2015)	Robot-assisted vs lap vs open inguinal hernia repairs for inpatients	Not stated	2960 (open), 2960 (lap), 1480 (robot); propensity matched	"HCUP-provided cost-to-charge ratios were used to calculate cost by multiplying total charges with cost-to-charge ratio. For dataset containing cost, years 2011 - 2014 for Iowa were dropped because no cost data was available."	$18,494 (robot) vs $14,738 (lap) vs $16,740 (open); p<0.0001 for robot vs open and lap comparisons	LOS: 5.0 (open), 3.6 (lap), 2.2 (robot); p<0.0001 for robot vs open and lap comparisons
Khoraki 2019[78]	Retrospective, single institution	Robot-assisted vs lap inguinal hernia repair	4	45 (robot) 138 (lap)	See footnote 1	Total hospital cost: $9994 (robot) vs $5995 (lap), p<0.01	Operative time: 116 min (robotic) vs 95 in (lap), p<0.01
Prabhu 2020[63]	Multi-institutional RCT	Robot-assisted vs lap TAPP	Not stated	54 lap 48 robot	Costs per case at each institution were reported as total cost, operating room cost (cost per min OR time per case), and disposable/ reusable cost, include disposable	Total cost $3258 (robot) vs $1421 (lap); p<0.001	Operative time (skin to skin) 75.5 min (robot) vs 40.5 min (lap), p<0.001

					materials and reusable materials - robotic instruments. Robotic and laparoscopic capital equipment cost were not amortized.		
Waite, 2015[65]	Retrospective, single institution	Robot-assisted vs laparoscopic TAPP repair	Not stated	24 lap 39 robotic	"institution financial department… included direct costs, facility net revenue, and contribution margin" Direct costs were variable costs of surgery (*ie*, mesh, disposable lap equipment, reposable robotic equipment). Capital costs (*ie*, robotic system, lap towers, and non-disposable equipment) **NOT** included.	Average direct cost per case was $3216 (lap) vs $3479 (robot), p=NS	Operative time was longer robotic (77.5 minutes vs 60.7 minutes, p=0.001)

Footnote 1: 3 separate cost analyses were performed: 1. Total hospital costs: estimated cost of anesthesia, operating room, and recovery in addition to the disposable supplies and medications used during surgery. A combination of case-level and time-based system (per 1/2 h increment) used to calculate cost of surgery. Case-level is determined by ASA, procedure complexity, and equipment and staff. 2. Total disposable supplies and categories costs: combined operating room usage with supply pricing. Each surgery had its disposable supplies usage queried. Amount and costs for trocars, fixation devices, meshes, medications, drapes, and all accessories and other disposable equipment were collected. Cost adjusted to 2017 dollars. 3. Capital and service cost of the Robotic da Vinci® Surgical Systems: actual cost of systems was obtained and its depreciation was calculated based on an estimated 6-year lifespan. Capital cost associated with utilizing the robot per case was calculated as total depreciation during the study period divided by number all robotic cases performed by all surgeons. Cost of maintenance services per case was added.

Summary of Findings

Five studies compared the costs of robot-assisted as compared to laparoscopic or open surgery for inguinal hernia repair. While there were significant limitations with the methodology, there is a consistent finding, including from randomized data, that the robot-assisted approach is more expensive than the laparoscopic and the open approach. How much more expensive is not known with precision. However, the lack of cost-effectiveness studies suggests that weighing the balance between the added cost against possible benefits and risks of the robot-assisted approach are not known.

Certainty of Evidence for Key Question 2B

Based on directness and consistency in the evidence, including from randomized data, we have moderate certainty that robot-assisted surgery is more expensive than laparoscopic or open surgery for inguinal hernia repair. As there were no formal cost-effectiveness analysis, no conclusion can be made in that regard.

KEY QUESTION 1C – VENTRAL HERNIA SURGERY: What is the clinical effectiveness of robot-assisted surgery compared to conventional laparoscopic or open surgery for ventral hernia repair?

We identified 21 publications that met the inclusion criteria for assessing clinical outcomes. There was only 1 RCT, which was a conference abstract comparing robot-assisted to laparoscopic ventral hernia repair.[85] The remaining 20 studies were observational studies, of which 7 studies compared robot-assisted ventral hernia repair to open repair only,[86-92] 11 studies compared robot-assisted surgery to laparoscopic surgery only,[76,93-102] and 2 studies compared robot-assisted surgery to both laparoscopic and open approaches.[103,104] Six studies included analysis of patients who underwent transversus abdominis release as a component of the ventral hernia repair.[86-88,90,92,101] The only RCT was a single institutional study from Brazil and included 38 subjects.[85] All of the observational studies were done in the United States; of these, only 4 were specified to be multi-institutional,[87,90,96,97] while 9 were specified to be from a single institution.[76,86,88,92,93,95,100-102] Eleven of the observational studies utilized retrospective data from prospectively maintained databases.[89-92,94,96,98,99,101,103,104] The studies varied in size from 25 to 46,799 subjects. Of the observational studies, 7 studies utilized matching of various preoperative patient or hernia characteristics in their outcome analysis.[87,89,90,96,97,99,103]

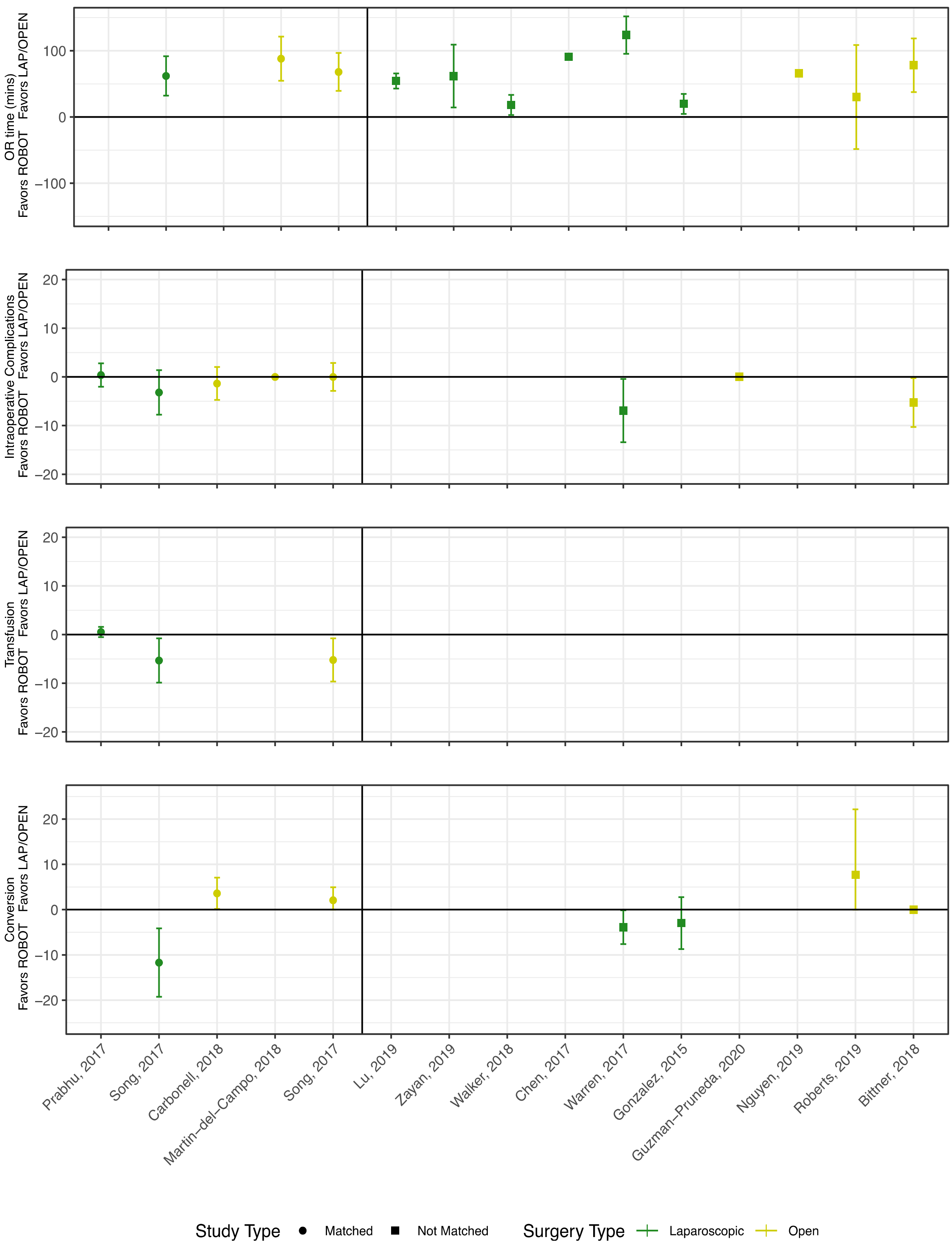
The RCT warrants specific mention.[85] It was very limited in terms of the data the authors presented and was only an abstract. The sample sizes were quite small, 19 in each arm. The study compared robot-assisted ventral hernia to laparoscopic, but other details of the operative techniques were not provided. They did not report on our intraoperative outcomes of interest (OR time, intraoperative complications, transfusions, or conversion to open surgery) or the majority of our postoperative short-term outcomes (LOS, complications, SSI, or readmissions). They did report (without actual supporting data) that "QOL before and after the procedures showed improvement in both groups and but in favor of the robot-assisted group as well as the gain in the abdominal wall function." They reported lower recurrence rate for robot group, 10.5% (2/19) as compared to 21.1% (4/19) at 1 year. One death was reported in the laparoscopic group. They did not comment on any deaths in the robot-assisted group. Therefore, this RCT was not abstracted along with the observational data analyzed below.

Figure 9 presents results for 4 intraoperative outcomes: OR time, intraoperative complications, transfusions, and conversion to open surgery. Fourteen observational studies were included in this subset of analysis.[76,86-88,90-93,95-97,100,101,103] One study compares robot-assisted surgery to both laparoscopic and open approaches,[103] while 7 studies only compare to laparoscopic,[76,93,95-97,100,101] and 6 studies only compare to open surgery.[86-88,90-92] Four studies[87,90,96,103] utilize preoperative patient characteristics for matching, while the remaining 8 do not utilize matching.

Of the 11 studies assessing OR time, all studies demonstrate a statistically significant increase with robot-assisted ventral hernia repair compared to open and laparoscopic approaches,[76,86-

[88,93,95,97,100,101,103] with the exception of 1 study that demonstrated no difference comparing robot to open repair.[92] Of the 7 studies assessing intraoperative complications,[86,87,90,91,96,101,103] 2 unmatched studies demonstrate a significantly decreased complication rate with robot-assisted ventral hernia repair compared to laparoscopic and open repairs,[86,101] and the remaining unmatched study demonstrated no difference in complication rate between robot-assisted and open repair.[91] The 4 matched studies do not demonstrate a significant difference in complication rate among the approaches.[87,90,96,103] Two matched studies were included in the analysis for transfusion,[96,103] of which 1 study demonstrated a significant decrease in transfusions in robot-assisted ventral hernia repair compared to both open and laparoscopic approaches,[103] while the other study did not demonstrate a difference between robot-assisted and laparoscopic surgeries.[96] Of the 6 studies included in the analysis for conversion,[86,90,92,95,101,103] 1 matched[103] and 1 unmatched[101] study each demonstrated a decreased conversion rate to open surgery with robot-assisted surgery compared to laparoscopy, while a third study[95] favored decreased conversion rates with robot-assisted surgery but was not significant. Of the 4 studies assessing robot-assisted conversion rates when compared to open ventral hernia repair, 1 matched study showed a significantly increased conversion rate of robot-assisted surgery,[90] while another matched study demonstrated a non-significant increase in conversion.[103] Of the remaining 2 unmatched studies, 1 showed a non-significant increase in conversion from robot-assisted surgery to open,[92] while there was no difference in the remaining study.[86]

Figure 9. Ventral Hernia Intraoperative Outcomes



Graphed is the point estimate and 95% confidence intervals for the difference in the indicated outcome between robot-assisted ventral hernia repair and either laparoscopic (green) or open (gold) approaches. Studies utilizing matching (circles) are listed in the left-hand side, while studies that did not utilize matching (squares) are listed on the right-hand side.

Figure 10 presents the results for 5 postoperative short-term outcomes: LOS, complications, surgical site infection (SSI), readmissions, and mortality. Nineteen observational studies were included in this subset of analysis.[76,86-88,90-104] Two studies compared robot-assisted surgery to both open and laparoscopic approaches,[103,104] 11 studies compared to only laparoscopy,[76,93-102] and 6 studies compared to only open surgery.[86-88,90-92] Five studies[87,90,96,99,103] utilized matching while the remaining 14 did not.

Of the 18 studies assessing outcomes for LOS,[76,86,87,90-104] 6 studies comparing the robot-assisted to laparoscopic approaches,[76,96,99,101,102,104] of which 2 were matched,[99,105] demonstrated a significantly lower LOS for the robot-assisted arm. All 7 studies comparing robot-assisted ventral hernia repair to the open approach,[86,87,90-92,103,104] of which 3 were matched,[87,90,103] also demonstrated a significantly lower LOS. Within the matched cohort, only the laparoscopic comparison arm of 1 study demonstrated no difference in LOS.[103] In contrast, 1 unmatched study demonstrated a small but statistically significant increase in LOS with robot-assisted surgery compared to laparoscopy.[97] However, the remaining 5 studies did not demonstrate a significant difference.[93-95,98,100]

Of the 13 studies assessing outcomes for complications,[87,90,92,93,95-101,103,104] 4 matched studies revealed a significantly lower rate of postoperative complications of robot-assisted ventral hernia repair compared to both laparoscopic and open approaches,[87,96,99,103] and 1 unmatched study demonstrated a lower robot-assisted complication rate compared to laparoscopy.[93] Only 1 matched study demonstrated a non-significant trend toward lower complication rates in the robot-assisted arm compared to open surgery.[90] In 1 unmatched study, robot-assisted ventral hernia repair demonstrated a slight but significant decrease in complication rate compared to the open approach, while within the same study, the robot-assisted surgery demonstrated a similarly slight but significant increase in complications when compared to laparoscopy.[104] The remaining 6 studies demonstrated no difference in complication rate in robot-assisted ventral hernia repair compared to laparoscopy or open surgery.[86,92,95,98,100,101]

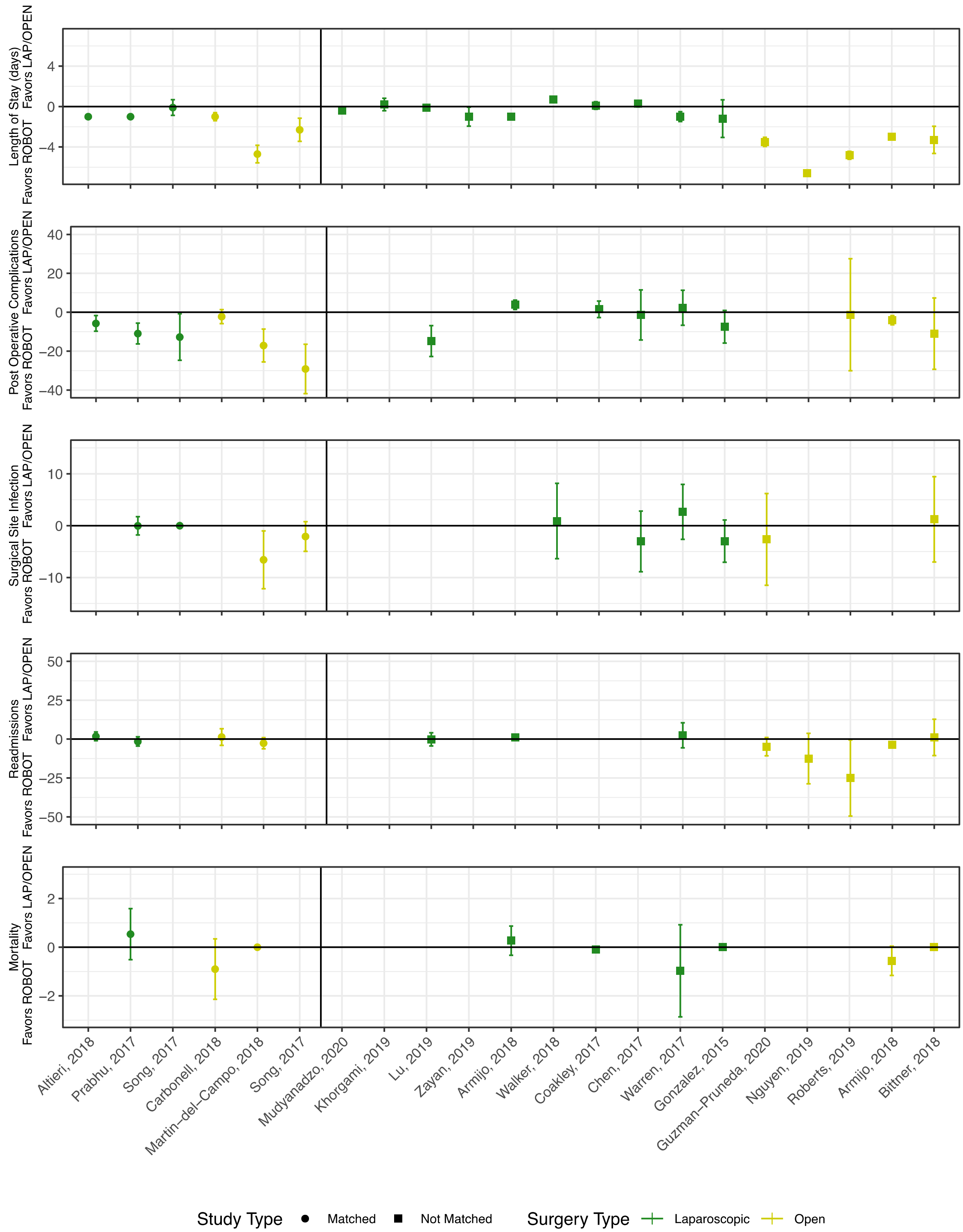
Of the 9 studies examining the outcome of SSI,[86,87,91,95-97,100,101,103] only 1 matched study[87] demonstrated a significantly lower SSI rate with robot-assisted surgery compared to open repair. In a matched study comparing robot-assisted ventral hernia repair to both open and laparoscopic approaches, there was a trend toward lower SSI with robot-assisted surgery when compared to open surgery, but there was no difference when compared to laparoscopic repair.[103] The remaining 7 studies did not demonstrate a significant difference among the approaches in SSI rates.[86,91,95-97,100,101]

Of the 11 studies assessing outcomes for readmissions,[86-88,90-93,96,99,101,104] 1 unmatched study demonstrated significant decrease in readmission rate following robot-assisted ventral hernia repair compared to open.[92] Two other unmatched studies demonstrated non-significant decreases in readmission following robot-assisted surgery compared to open.[88,91] The remaining 4 studies comparing robot-assisted to open surgery[86,87,90,104] including 2 matched studies,[87,90] demonstrated no difference. There was no difference in readmission rate in the 5 studies comparing robot-assisted ventral hernia repair to laparoscopy,[93,96,99,101,104] of which 2 were matched.[96,99]

Of the 8 studies assessing mortality, the data was overall mixed with none of the studies demonstrating significantly different mortality rates among the approaches.[86,87,90,95,96,98,101,104]

While 1 matched[90] and 1 unmatched[104] study demonstrate non-significant trends toward decreased mortality rates with the robot-assisted approach when compared to open surgery, another pair of matched[87] and unmatched[86] studies showed no difference in mortality between these approaches. When comparing robot-assisted ventral hernia repair with the laparoscopic approach, 2 studies,[96,104] of which 1 was matched,[96] had a trend toward increased mortality with robot, while 1 unmatched study[101] trended toward decreased mortality with robot, and the remaining 2 unmatched studies demonstrated no difference between these approaches.[95,98]

Figure 10. Ventral Hernia Postoperative Short-term Outcomes

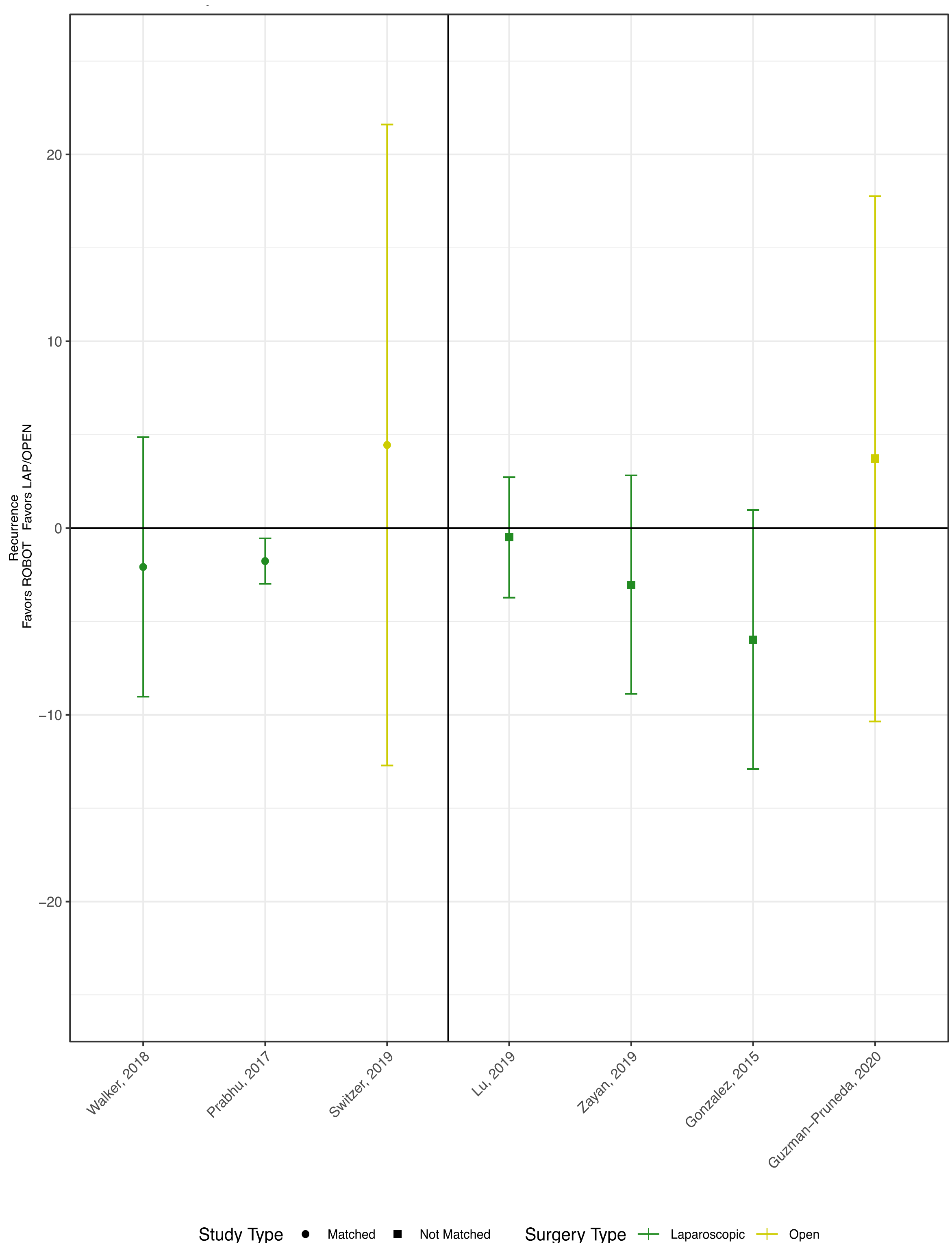


Graphed is the point estimate and 95% confidence intervals for the difference in the indicated outcome between robot-assisted ventral hernia repair and either laparoscopic (green) or open (gold) approaches. Studies utilizing propensity matching (circles) are listed in the left-hand side, while studies that did not utilize propensity matching (squares) are listed on the right-hand side.

Figure 11 presents the results for ventral hernia recurrence, the only postoperative long-term outcome for ventral hernia repair. Of the 7 studies included in this analysis,[89,91,93,95-97,106] 5 studies compared robot-assisted surgery to the laparoscopic approach,[76,93,95-97] while 2 studies[89,91] compared the robot-assisted approach to the open approach. Only 1 matched study demonstrated a slight but significantly decreased recurrence rate following robot-assisted ventral hernia repair compared to laparoscopic repair,[96] while the other matched study[97] and 3 unmatched studies[76,95,97] demonstrated a trend toward decreased hernia recurrence compared to laparoscopic repair without significance. The 2 studies comparing robot-assisted to open approaches revealed a non-significant trend toward increased recurrence rate.[89,91]

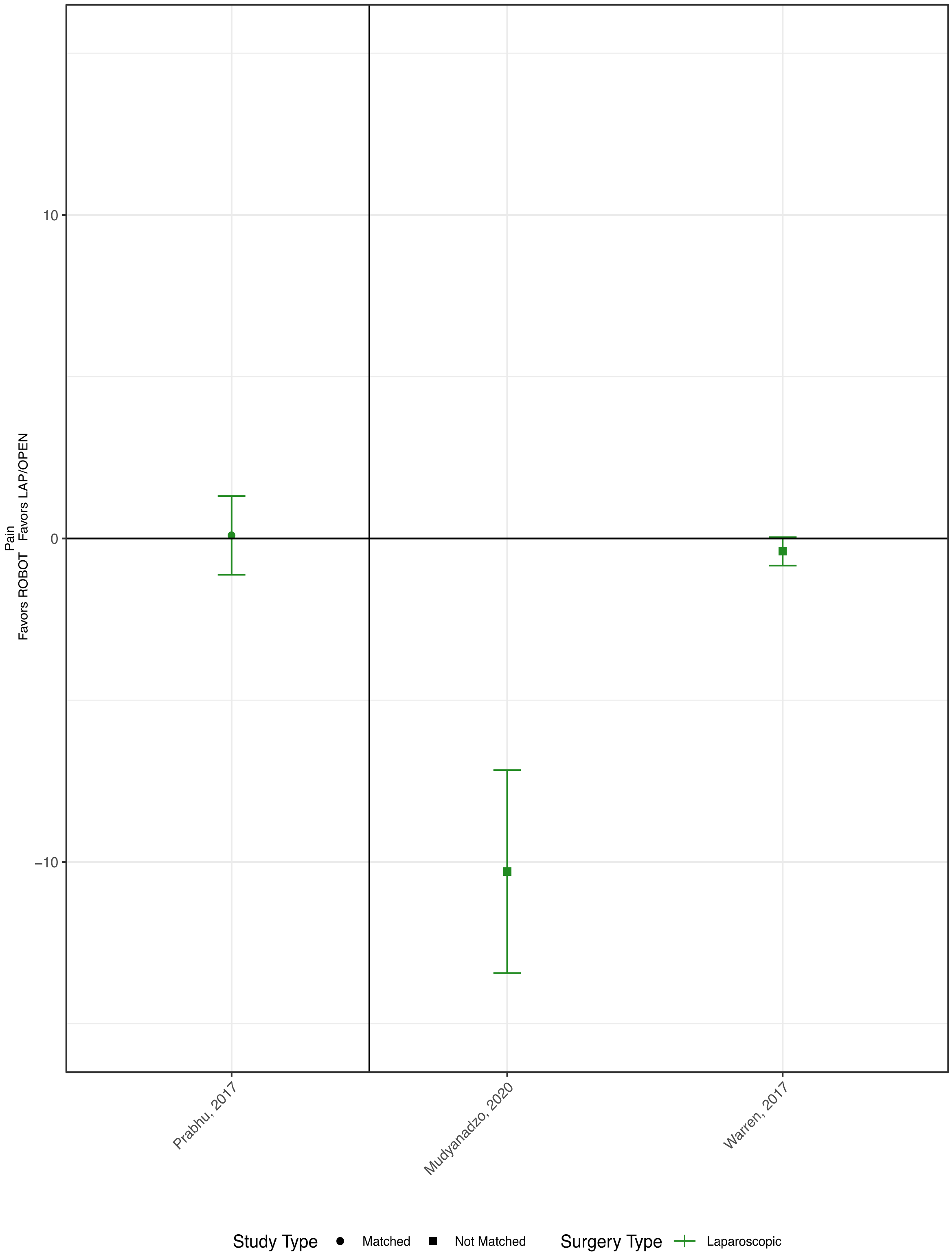
Figure 12 presents the results for postoperative pain following ventral hernia repair. Only 3 studies were included in this analysis,[96,101,102] which all compared robot-assisted surgery to laparoscopic repair. The matched study demonstrated no difference between the approaches,[96] while 1 unmatched study demonstrated a significant decrease in pain following robot-assisted ventral hernia repair,[102] and the remaining unmatched study favored the robot-assisted approach without significance.[101]

Figure 11. Ventral Hernia Postoperative Long-term Outcomes



Graphed is the point estimate and 95% confidence intervals for the difference in the indicated outcome between robot-assisted ventral hernia repair and either laparoscopic (green) or open (gold) approaches. Studies utilizing matching (circles) are listed in the left-hand side, while studies that did not utilize matching (squares) are listed on the right-hand side.

Figure 12. Ventral Hernia Postoperative Pain Outcomes



Graphed is the point estimate and 95% confidence intervals for the difference in the indicated outcome between robot-assisted ventral hernia repair and laparoscopic (green) approaches. Studies utilizing matching (circles) are listed in the left-hand side, while studies that did not utilize matching (squares) are listed on the right-hand side.

Summary of Findings

Operative room time was significantly longer in robot-assisted ventral hernia repair compared to both the laparoscopic and open approaches in all but 1 study included. There was no evidence of a difference in intraoperative complication rate among the 3 approaches. There is a possible trend toward decreased transfusion rate with robot-assisted surgery compared to laparoscopic and open repairs, with 1 matched study demonstrating a significant difference favoring robot-assisted surgery and another demonstrating no difference. With regard to conversion to open surgery, most studies demonstrate a decreased rate of conversion with robot-assisted surgery compared to the laparoscopic approach. Robot-assisted ventral hernia repair appears to have significantly decreased LOS compared to open repair; however, this decrease may be less significant when compared to laparoscopic repair. There is a likely decrease in postoperative complication rate following robot-assisted repair compared to both laparoscopic and open approaches based on the results of matched studies (unmatched studies do not support this trend). There may be a small signal favoring robot-assisted ventral hernia repair for reducing postoperative SSIs compared to open surgery; however, there does not appear to be evidence of a difference when compared to the laparoscopic approach. There is no evidence of a difference in readmission or mortality rates among the approaches. In terms of hernia recurrence, the 2 studies comparing robot-assisted ventral hernia repair to open surgery demonstrated no difference, while there may be a slight trend favoring robot-assisted ventral hernia repair compared to laparoscopic surgery based on results from 1 matched study. Finally, there may be a small signal of decreased postoperative pain favoring the robot-assisted approach when compared to the laparoscopic approach based on significant findings from 1 unmatched study. However, the matched study does not support this.

Certainty of Evidence for Key Question 1C

All studies included in this analysis were observational studies, which decreased the overall certainty of evidence. The 1 available RCT was too limited in detail to use in our analysis. We judged the certainty of evidence for the outcome of increased OR time for robot-assisted ventral hernia repair compared to open and laparoscopic repairs as high due to the consistency among nearly all studies included in this analysis, except for 1 unmatched study. We judged the certainty of evidence that there is no difference in intraoperative complications among the approaches as low due to inconsistency and imprecision. We judged the certainty of evidence that there is the same or slightly decreased rate of transfusion for robot-assisted surgery compared to open and laparoscopic hernia repairs as low because the few matched studies that assessed this particular outcome were inconsistent and imprecise. We judged the certainty of evidence that there is a decreased conversion rate to open surgery with robot-assisted surgery compared to laparoscopic surgery as low, as the data was consistent but imprecise. We judged the certainty of evidence that robot-assisted ventral hernia repair decreased LOS compared to open surgery and less significantly when compared to laparoscopic surgery as moderate, based on preciseness and consistency across matched and unmatched studies. Both outcomes of postoperative complications and SSI were deemed to have low certainty of evidence due to the inconsistency and imprecision of the data. Mortality and readmissions were judged to be equivalent across the 3 approaches with moderate certainty of evidence. There is low certainty that there may be a minimal difference in hernia recurrence favoring robot-assisted ventral hernia repair compared to laparoscopy and no difference compared to open surgery. Finally, there is a low certainty that there is no difference in postoperative pain following ventral hernia repair in the 3 approaches, based on only 2 studies.

Table 5. Certainty of Evidence for Ventral Hernia Repair Studies

Outcome	Study Limitations	Consistency	Directness	Precision	Certainty of Evidence
Intra-operative					
Operating Room Time Robot > Open/ Laparoscopy	Unmatched observational studies: High Matched observational studies: Moderate	Consistent	Direct	Precise	High
Intraoperative Complications Robot = Open/ Laparoscopy	Unmatched observational studies: High Matched observational studies: Moderate	Inconsistent	Direct	Imprecise	Low
Transfusion Robot < Open/ Laparoscopy	Matched observational studies: Moderate	Inconsistent	Direct	Imprecise	Low
Conversion to Open Surgery Robot < Laparoscopy Robot > Open	Unmatched observational studies: High Matched observational studies: Moderate	 Consistent Consistent	 Direct Direct	 Imprecise Imprecise	 Low Low
Postoperative Short-term					
Length of Stay Robot < Open/ Laparoscopy	Unmatched observational studies: High Matched observational studies: Moderate	Consistent	Direct	Precise	Moderate
Postoperative Complications Robot < Open/ Laparoscopy	Unmatched observational studies: High Matched observational studies: Moderate	Inconsistent	Direct	Imprecise	Low
Surgical Site Infection Robot < Open Robot = Laparoscopy	Unmatched observational studies: High Matched observational studies: Moderate	 Inconsistent Inconsistent	 Direct Direct	 Imprecise Imprecise	 Low Low
Readmissions Robot = Open/ Laparoscopy	Unmatched observational studies: High Matched observational studies: Moderate	Consistent	Direct	Imprecise	Moderate
Mortality Robot = Open/ Laparoscopy	Unmatched observational studies: High Matched observational studies: Moderate	Consistent	Direct	Imprecise	Moderate
Postoperative Long-term					
Hernia Recurrence Robot = Open/ Laparoscopy	Unmatched observational studies: High Matched observational studies: Moderate	Consistent	Direct	Imprecise	Low
Pain					
Pain Robot < Laparoscopy	Unmatched observational studies: High	Consistent	Direct	Imprecise	Low

Outcome	Study Limitations	Consistency	Directness	Precision	Certainty of Evidence
	Matched observational studies: Moderate				

KEY QUESTION 2C – VENTRAL HERNIA SURGERY: what is the cost-effectiveness of robot-assisted surgery compared to conventional laparoscopic or open surgery for ventral hernia repair?

We identified 6 studies that compared robot-assisted ventral hernia to other approaches and provided some data on costs. Two were single institution studies,[103,107] 2 used the National Inpatient Sample,[94,98] 1 used the Vizient administrative database,[104] and 1 used a surgical registry.[101] One study reported only cost data and no clinical outcomes.[107] All compared robot-assisted to laparoscopic surgery, with 2 also including an open comparison. Three studies found the robot approach to be more expensive than laparoscopic surgery, 1 found the robot-assisted approach had a non-statistically significant higher cost than laparoscopy, and 2 found the robot-assisted surgery and laparoscopy were similar with respect to costs.

As with inguinal hernia, the methodology of the included studies was very limited, especially as it relates to details regarding how costs were derived. Evidence of the diversity of methods used is the fact that cost estimates ranged from as low as $4,000 to as high as $61,000 for the cost of the robot. This reflects the fact that when measuring costs, investigators must be very specific about the perspective (cost vs charge), time frame (just OR, OR and hospital stay, hospital stay + 30/90 days), and explicit details about what is and is not included in cost estimates (direct vs indirect, variable vs fixed, *etc*). None of the studies included all of these details. Most studies provided less than 1 sentence about how cost estimates were derived. Several studies relied on administrative databases and used cost-to-charge ratios to estimate hospital costs. Previous research has demonstrated that these measures are prone to bias, especially in surgery.[11,108] It is unlikely that these methods adequately capture the nuance of cost intrinsic to the robot, such as the amortization of the purchase price, the service contract, and the semi-variable cost of the surgical instruments. As with the inguinal hernia studies, none of these studies comment on staff costs nor did they follow reporting guidelines (*eg*, Second Panel on Cost Effectiveness, CHEERS). Two of the included studies did find the operative time was longer for the robot-assisted approach compared to the laparoscopic approach, with 1 study finding the operative times of robot-assisted cases were approximately double those of the laparoscopic cases (240 minutes versus 120 minutes). When dealing with large differences in time, consideration must be given to staffing costs and, perhaps more importantly, the opportunity cost of not performed cases.

Table 6. Evidence Table for Ventral Hernia Cost Studies

Author, Year, Number	Study Design, Number of Institutions	Comparison	Number of surgeons	Sample Size	Source of cost data	Cost data	Misc. outcomes
Armijo, 2018[104]	Retrospective review of Vizient database	Robot-assisted vs laparoscopic vs open ventral hernia repair	Not stated	39,505 open 6,829 lap 465 robotic	"Ratio of cost-to-charge method applied for estimating cost of patient care…"	Total direct cost: $9000 (open), $7000 (lap), $10,000 (robot)	Median LOS was 5 days (open), 3 days (lap), 2 days (robot)
Coakley, 2017[98]	Retrospective review of National Inpatient Sample (2008-2013)	Robot-assisted vs laparoscopic ventral hernia repair	Not stated	351 robotic 32,243 lap	"Total hospital charges…"	Adjusted model (controlling for CCI, geographic, public vs private etc) mean charges were $41,911 (lap) vs $61,205 (robot)	LOS no different lap vs robot (3.4 days lap, 3.5 days robot, p=NS)
Khorgami, 2019[94]	Retrospective review of National Inpatient Sample (2012-2014)	Robot-assisted vs laparoscopic ventral hernia repair	Not stated	3600 lap 99 robotic	"Hospital total charges were converted to cost estimates using hospital specific cost-to-charge ratios provided by HCUP. Admissions with total charges below 0.1 percentile or above 99.9 percentile were considered outliers and excluded from analysis."	$10,739 (lap) vs $13,441 (robotic); p-value not provided	LOS 2.7 days (lap) vs 2.9 days (robot); p-value not provided
Song, 2017[103]	Retrospective review, Premier Perspectives Database, Abstract only	Robot-assisted vs lap vs open elective ventral hernia repairs in patients with BMI > 30	Not stated	2 samples (depending on comparison)… 94/94 robot vs lap and 96/96 robot vs open	"total cost included direct cost and overhead cost and was adjusted for inflation to 2015 US dollars"	All were the same… approximately $10,500 (p=NS)	OR time was 231 min (robot), 169 min (lap), and 163 min (open)… robot and lap (<.0001) LOS was 3.1 days (robot), 3.2

							days (lap), 5.3 days (open); robot vs open (p=0.003)
Tan, 2017[107]	Retrospective review, single institution, Abstract only	Robot-assisted vs laparoscopic ventral hernia repairs	1	46 robotic 47 lap	Primary outcome: "disposable operating room costs" Secondary outcomes: "technical direct costs such as costs from the laboratory or pharmacy…"	Median total variable costs were $4,551 (lap) versus $4362 (robot), p=NS; OR median costs were $3,391 (lap) versus $3,095 (robot), p=NS	Results state no difference in OR time or LOS but no data
Warren, 2017[101]	Retrospective review, Americas Hernia Society Quality Collaborative (multi-institutional)	Robot-assisted vs laparoscopic ventral hernia repair	Not stated	103 lap 53 robotic	No details provided	Mean direct hospital cost $13,943 (lap) vs $19,532 (robotic), P=NS	Operative time 121 min (lap) vs 245 min (robotic), p<0.001

Summary of Findings

There are only a handful of cases comparing the costs of robot-assisted versus laparoscopic or open surgery for ventral hernia repair. All had significant limitations, primarily surrounding the cost methodology used. However, 4 of the 6 studies reported that the robot-assisted approach was more expensive than either the laparoscopic or open approach (with large effect size) and the other 2 studies reported no difference in cost as compared to laparoscopic repair.

Certainty of Evidence for Key Question 2C

We have low certainty that robot-assisted surgery is more expensive than laparoscopic ventral hernia repair or open ventral hernia repair based on inconsistency and imprecision (studies were all observational). We have insufficient data to render a statement regarding the cost of robot-assisted versus the other surgical approaches. Importantly, since there were no formal cost-effectiveness analyses, no conclusion can be made in this regard as well.

SUMMARY AND DISCUSSION

SUMMARY OF EVIDENCE BY KEY QUESTION

Key Question 1A: What is the clinical effectiveness of robot-assisted surgery compared to conventional laparoscopic or open surgery for cholecystectomy?

In general, OR time was longer in patients treated with robot-assisted cholecystectomy compared to laparoscopic cholecystectomy. While not always statistically significant, data are consistent across RCTs and observational studies. There was no evidence of differences in total intra-operative complications or conversions, and most studies had point estimates close to the null value. Only 5 studies reported common bile duct injuries, and there was no evidence of a difference between robot-assisted cholecystectomy and laparoscopic cholecystectomy. Most studies did not demonstrate a significant difference in LOS, postoperative complications, or surgical site infections. Pain was variable among the studies and did not demonstrate a pattern. The rate of incisional hernia may be higher in the robot-assisted cholecystectomy cohort when performed using a single-port compared to a multi-port laparoscopic surgery. This finding is not unexpected and may not be an appropriate comparison, as the single-port robot-assisted cholecystectomy requires a larger incision than the smaller incisions needed for the multi-port laparoscopic cholecystectomy. Studies comparing single-port robot-assisted assisted cholecystectomy and single-port laparoscopic cholecystectomy were not different in hernia outcomes. This is an important consideration, since the single-port approach with robot-assisted cholecystectomy or laparoscopic cholecystectomy involves a larger incision and confers a higher risk for developing an incisional hernia. Thus, the interpretation of this finding may be related to single-port versus multi-port, not robot versus laparoscopic.

Key Question 2A: What is the cost-effectiveness of robot-assisted surgery compared to conventional laparoscopic or open surgery for cholecystectomy?

While there are a number of studies comparing the cost-effectiveness of robot-assisted versus laparoscopic surgery for cholecystectomy, all had significant limitations, primarily surrounding the cost methodology. None were formal cost-effectiveness analysis studies. Nevertheless, there was an almost unanimous finding, including in the randomized data, that the robot-assisted approach is more expensive than the laparoscopic approach. We therefore have moderate certainty that robot-assisted surgery is more expensive than laparoscopic cholecystectomy.

Key Question 1B: What is the clinical effectiveness of robot-assisted surgery compared to conventional laparoscopic or open surgery for inguinal hernia repair?

Operative room time was longer in patients treated with robot-assisted inguinal hernia repair compared to laparoscopic and open repair, particularly for unilateral repairs. In terms of LOS, there may be a signal of a small benefit favoring the robot-assisted approach compared to open surgery for inpatient stays. There does not appear to be a signal of benefit with regard to SSI for the robot-assisted approach compared to laparoscopic or open surgery. There may be a small signal of benefit for lower readmissions with the robot-assisted approach for unilateral hernias. Most studies demonstrated no difference among approaches when assessing complications and postoperative pain. There was no difference in hernia recurrence among all approaches.

Key Question 2B: What is the cost-effectiveness of robot-assisted surgery compared to conventional laparoscopic or open surgery for inguinal hernia repair?

Only 5 studies compared costs of robot-assisted compared to laparoscopic or open surgery for inguinal hernia repair. All had significant limitations, primarily surrounding the cost methodology. Robot-assisted surgery was more expensive in these studies as compared to laparoscopic or open inguinal hernia repair. Based on somewhat limited directness and consistency in the evidence, we have low certainty that robot-assisted surgery is more expensive than laparoscopic or open surgery for inguinal hernia repair. Importantly, since there were no formal cost-effectiveness analyses, no conclusion can be made in this regard as well.

Key Question 1C: What is the clinical effectiveness of robot-assisted surgery compared to conventional laparoscopic or open surgery for ventral hernia repair?

Operating room time was longer in patients who underwent robot-assisted ventral hernia repair compared to both the open approach and laparoscopic approach. This was an almost universal finding among all the studies evaluating this outcome. Conversion to open surgery from a robot-assisted approach may be less than from a laparoscopic approach. This finding was demonstrated in 1 matched[103] and 1 unmatched study[101] with a third study[95] showing no difference. LOS also may be favored by performing a robot-assisted surgery for ventral hernia. This was a statistically significant difference between robot-assisted and open ventral hernia repair; however, this effect was not shown when compared to the laparoscopic approach. There was no evidence of differences in readmissions, SSI, postoperative complications, and mortality. The outcome of recurrence was evaluated in 1 matched study[96] and 5 unmatched studies[76,89,93,95,97] showing no significant difference except in the matched study. Only 2 studies evaluated postoperative pain, which showed no difference between the groups of patients.[96,101]

Key Question 2C: What is the cost-effectiveness of robot-assisted surgery compared to conventional laparoscopic or open surgery for ventral hernia repair?

There are a handful of cases comparing the costs of robot-assisted versus laparoscopic or open surgery for ventral hernia repair. All had significant limitations, primarily surrounding the cost methodology. However, 4 of the 6 studies reported that the robot-assisted approach was more expensive than either the laparoscopic or open approach (with large effect size) and the other 2 studies reported no difference in cost as compared to laparoscopic repair. As seen for cholecystectomy and inguinal hernia, no cost-effectiveness studies were identified.

LIMITATIONS

Publication Bias

We were not able to test for publication bias and can make no conclusions about its possible existence. However, we believe it is extremely unlikely that there exists a high-quality randomized trial of robot-assisted surgery versus other surgical approaches that we did not identify, and has similarly escaped detection by all other experts in this field. There are probably a plentitude of observational experiences about robotic therapies, from individual institutions, that have never been published, and the published literature likely represents only a small fraction of what could be known using observational studies.

Study Quality

The randomized trials for were judged to be at low risk of bias for short-term outcomes, like intraoperative and postoperative outcomes. They were judged to be at moderate risk of bias for longer-term outcomes. Likewise, the observational studies were judged to be at moderate risk of bias (due to their non-random assignment of treatments) for short-term outcomes and high risk of bias for longer-term outcomes.

Heterogeneity

As mentioned, the studies were very heterogeneous across patient and technique factors as well as how the outcomes were measured. Since we only found 4 RCTS for cholecystectomy, 1 for inguinal hernia repair, and 1 small RCT for ventral hernia repair, the vast majority of our data was observational. There are potential strong selection biases by the surgeons for when they would choose to perform a robot-assisted case over the standard approaches – which often leads to differences in the comparative groups, which we saw in the studies included in our review. The technique used for the robot-assisted approach is also different – how the mesh is secured, fascial closure, bilateral repair, or number of ports.

Some outcomes had heterogeneous measurements across studies. These included: OR time, LOS, and pain. OR time was most commonly reported as skin cut time to closure, but others reported the room time, console time, or didn't define their measurement. Length of stay was also challenging to compare across studies as these operations could be performed as outpatient or inpatient and there was often a mix of time scale between or within studies. Pain as an outcome was reported using a variety of measures: different scales, variable time intervals, receipt of pain medications, time needing pain medication, and occurrence of chronic nerve pain. This greatly limited the ability to compare results across studies.

Applicability of Findings to the VA Population

Only 2 studies were specific to VA populations – 1 for cholecystectomy[29] and 1 for inguinal hernia repair[67] – therefore strong conclusions from this data cannot be made. Unfortunately, we are not aware of any robotic cost data within the VA, but utilization data is available and this may serve as a first step towards future research in this area.

However, the applicability of these results to VA populations may depend on both the similarity of the patients studied to VA patients and the experience of the surgical teams using the robot to VA surgical team experience. Yet the benefits for robot-assisted approach may still be realized despite patient-level differences (VA patient population has greater burden of comorbidities than the general population), which will need to be confirmed in future studies. Urology as a surgical field has widely adopted robot-assisted surgery, so this experience will likely translate well into the expansion of robot-assisted approach to general surgery in the VA setting.

Research Gaps/Future Research

Numerous research gaps are apparent. There is a need for randomized data or propensity matching that addresses patient- and technique-related factors. The variability in the use of the robot-assisted approach based on these factors currently limits the ability to compare across study arms, as variations at baseline or differences in how the operation was performed are large and may likely be responsible for realized clinical differences or lack thereof. Importantly, there are advantages of the robot that are clear and notable – enhanced, three-dimensional visualization, augmented dexterity and range of motion, reduction of tremor, to name a few. The heterogeneous nature of the studies limited the ability to show how these features translate into better clinical outcomes. Studies that control for key patient factors, case complexity, technical aspects of procedures, and surgeon experience may provide insight into this overarching question. Additionally, adequate long-term follow-up for certain outcomes is greatly needed. Several areas warrant specific discussion.

Surgeon Learning Curve

The surgeon learning curve is a well-characterized surgical concept that has similarly been applied to robot-assisted surgery. As with any new platform the need for training, practice, and experience is needed. Even open surgical procedures, such as pancreatectomy, suffer from inexperienced surgeons that require tutelage before displaying mastery of the technique. The advent of laparoscopy more than 30 years ago brought this concept more into the forefront and showed the impact of surgeon learning curves on clinical patient outcomes. Likewise, surgeon learning curve for robot-assisted cases is a multifaceted issue. Previous reviews found that the surgeon experience (*ie*, ability as a function of cases completed) is fluid, as it has multiple phases and surgeons tend to add increasingly complex patient cases as they gain experience.[1] In our review, we found that 90% of the studies for robot-assisted cholecystectomy acknowledged the possibility of a learning curve; however, only 5/46 provided data/assessment (and findings on OR time and incisional hernia occurrence were mixed).[22,23,29,34,37] A learning curve impact may likely vary by procedure as well. Research assessing surgeon experience needs to include a variety of clinical outcomes, not just efficiency such as OR time. With emerging technologies, research should routinely comment on and address the potential impact the level of experience of the surgeon or surgeons played.

Resident Training

Robotics as an evolving technology is also changing how surgical residents are educated. Furthermore, faculty surgeons need to gain their own experience while balancing training residents. 1 recent survey of program directors by Tom et al found that a 92% of programs have residents participating in robot-assisted surgery, while 68% offer formal curriculum; 44% track residents' robot-assisted experience, and about half (55%) recognize curriculum training completion.[109] Another study also found wide variations "in requisite components, formal credentialing, and case tracking and role of simulation training".[110] There is also no standardized approach on how to incorporate this training based on level of trainee. Overall, there is a need to adopt a standardized training curriculum and document resident competency.[111]

Long-term Follow-up

Our work identified a lack of high-quality evidence with adequate long-term follow-up and sufficient statistical power to properly assess clinical outcomes between the operative approaches for inguinal hernia repair and ventral hernia repairs. For hernia repairs, outcomes of interest need to include recurrent hernias beyond 1 year, long-term pain, and functional status. Only 1 small RCT was found for ventral hernia repair, none for inguinal, and it only reported on 1 main outcome of interest. The data we found was too limited to provide conclusions in this regard.

Cholecystectomy Research Gaps

Our review focused on use of robot-assisted surgery for benign, elective gallbladder disease. However, there is a need for future studies on cholecystectomy for non-benign pathology and emergent cases. As the robot-assisted technique is becoming more common, certain institutions are beginning to use it for cancer cases and non-elective surgeries, which are notably more complex. Given the differences in patient populations that experience these indications and the higher rates of complications for non-elective surgeries, the results from our study may not be generalizable to these populations. In fact, the robot-assisted approach may prove to be particularly advantageous for these more complex cases. The study of differences in cancer outcomes, and morbidity, for robot-assisted versus laparoscopic and open surgery is essential. As such, future research may consider expanding this review to examine different indications for cholecystectomy.

Inguinal Hernia and Ventral Hernia Repair Research Gaps

Specific to hernia repairs, the robot-assisted approach may offer several technical advantages. For inguinal hernias, the potential for avoiding tacks or even the need for suturing mesh (sutureless mesh) may lead to less postoperative acute and chronic pain. For ventral hernia, the robot-assisted approach with improved suturing technique can also forego placement of tacks as well as possibly decrease recurrent hernia formation. Unfortunately, these technical details were not uniformly available across the studies in our review and outcomes were typically not reported by these factors. As such, it was not possible to determine their specific roles. Additionally, baseline pain was often not reported, perioperative quality of life and pain data were sparse, and long-term data on chronic pain and recurrence were rare. Standardized reporting in future work is needed in order to sufficiently assess pain outcomes. Guidance should be provided on reporting technical aspects of the repair and requirements for clinical outcome assessment – for instance, specific time intervals, tools for assessing pain, and amount of pain medications taken.

Ergonomics for the Surgeon

An important issue that deserves study is the impact of the robot-assisted approach on the physical stress on the surgeon performing the operation. There is a high rate of musculoskeletal disorders attributed to poor ergonomics of laparoscopic surgery as well as the open approach. There are those that claim robot-assisted surgery ergonomics are superior, leading to decreased physical stress and workload. However, there is also growing evidence that a prolonged time sitting at the robot-assisted console adds new physical challenges as well.[112] Two recent studies reported physical discomfort and symptoms[113] or poor posture[114] in over half of surgeons. Although data are sparse, it would be a valuable area for future research. While challenging to study, the outcomes would need to be comparative, long-term (5 year plus) and would require assessing detailed quality of life, assessment of chronic physical injuries, and longevity of operating over a career.

Future Innovation in Surgical Robotics

An overwhelming number of the studies in our review used the da Vinci system from Intuitive (only 1 study used the Senhance robot).[22] The robotic field is changing soon, as a number of new robotic platforms are becoming available; there are 8 with FDA approval, and more pending approval.[5] These will bring with them potentially new advantages (*eg*, improved computer optics, machine learning, and automation) and possibly new challenges (*eg*, different technology with new learning curves, unknown impact on patient outcomes). Future research will be critical to assess the differences between these technologies. With these new market forces, there is anticipation for reduced cost as well.

Conflict of Interest

It is notable that reporting bias in robot-assisted surgery research has been identified. A recent study found that author payments from Intuitive were not declared in more than half (52%) of robot-assisted surgery research,[115] and they reported more positive findings as compared to those that did declare their conflict of interest (COI) payments. There is a need to ensure full disclosure of COI with more accountability and journals may want to adopt standardized processes to achieve better transparency.

Costs

Lastly, the lack of well-designed comparative studies also limits evaluations of cost. There is a need for standardized approaches to assess cost, which would apply to all 3 of these robot-assisted operations (*ie*, analytics approach, consistent definitions of cost, how upfront capital was accounted for, how to adjust for training staff, *etc*). Along these lines, formal cost-effectiveness studies that weigh the benefits and risks along with cost are needed.

Conclusions

Across 3 common general surgery procedures there is evidence that OR time is longer for the robot-assisted approach, and some signals that select intraoperative and postoperative complications are more favorable with the robot-assisted approach based on the operation. Overall, the studies were heterogeneous in terms of patient characteristics and how the operations were performed and definitive conclusions cannot be made. Cost is probably higher across these procedures, but the balance between the added expense and potential gains in effectiveness are unknown, until we adopt better, standardized methods of assessment.

REFERENCES

1. Pernar LIM, Robertson FC, Tavakkoli A, Sheu EG, Brooks DC, Smink DS. An appraisal of the learning curve in robotic general surgery. *Surgical endoscopy.* 2017;31(11):4583-4596.
2. Childers CP, Maggard-Gibbons M. Estimation of the Acquisition and Operating Costs for Robotic Surgery. *JAMA.* 2018;320(8):835-836.
3. Tsui C, Klein R, Garabrant M. Minimally invasive surgery: national trends in adoption and future directions for hospital strategy. *Surgical endoscopy.* 2013;27(7):2253-2257.
4. Rutkow IM. Demographic and socioeconomic aspects of hernia repair in the United States in 2003. *The Surgical clinics of North America.* 2003;83(5):1045-1051, v-vi.
5. Peters BS, Armijo PR, Krause C, Choudhury SA, Oleynikov D. Review of emerging surgical robotic technology. *Surgical endoscopy.* 2018;32(4):1636-1655.
6. Alemzadeh H, Raman J, Leveson N, Kalbarczyk Z, Iyer RK. Adverse Events in Robotic Surgery: A Retrospective Study of 14 Years of FDA Data. *PLoS One.* 2016;11(4):e0151470.
7. Tsai AY, Selzer DJ. Single-port laparoscopic surgery. *Advances in surgery.* 2010;44:1-27.
8. Cianci S, Rosati A, Rumolo V, et al. Robotic Single-Port Platform in General, Urologic, and Gynecologic Surgeries: A Systematic Review of the Literature and Meta-analysis. *World journal of surgery.* 2019;43(10):2401-2419.
9. Higgins JP AD, Gøtzsche PC, et al. The Cochrane Collaboration's tool for assessing risk of bias in randomised trials. *BMJ.* 2011:343:d5928.
10. Sterne JA HM, Reeves BC, et al. . ROBINS-I: a tool for assessing risk of bias in non-randomised studies of interventions. *BMJ.* 2016:355:i4919.
11. GRADE working group. 2014; http://www.gradeworkinggroup.org/.
12. Bittner Iv JG, Cesnik LW, Kirwan T, Wolf L, Guo D. Patient perceptions of acute pain and activity disruption following inguinal hernia repair: a propensity-matched comparison of robotic-assisted, laparoscopic, and open approaches. *Journal of robotic surgery.* 2018;12(4):625-632.
13. Grochola LF, Soll C, Zehnder A, Wyss R, Herzog P, Breitenstein S. Robot-assisted versus laparoscopic single-incision cholecystectomy: results of a randomized controlled trial. *Surgical endoscopy.* 2019;33(5):1482-1490.
14. Heemskerk J, Zandbergen HR, Keet SW, et al. Relax, it's just laparoscopy! A prospective randomized trial on heart rate variability of the surgeon in robot-assisted versus conventional laparoscopic cholecystectomy. *Digestive surgery.* 2014;31(3):225-232.
15. Kudsi OY, Castellanos A, Kaza S, et al. Cosmesis, patient satisfaction, and quality of life after da Vinci Single-Site cholecystectomy and multiport laparoscopic cholecystectomy: short-term results from a prospective, multicenter, randomized, controlled trial. *Surgical endoscopy.* 2017;31(8):3242-3250.
16. Pietrabissa A, Pugliese L, Vinci A, et al. Short-term outcomes of single-site robotic cholecystectomy versus four-port laparoscopic cholecystectomy: a prospective, randomized, double-blind trial. *Surgical endoscopy.* 2016;30(7):3089-3097.
17. Albrecht R, Haase D, Zippel R, Koch H, Settmacher U. [Robot-assisted surgery - Progress or expensive toy? : Matched-pair comparative analysis of robot-assisted cholecystectomy vs laparoscopic cholecystectomy]. *Der Chirurg; Zeitschrift fur alle Gebiete der operativen Medizen.* 2017;88(12):1040-1045.

18. Main WPL, Mitko JM, Hussain LR, Meister KM, Kerlakian GM. Robotic versus Laparoscopic Cholecystectomy in the Obese Patient. *The American surgeon.* 2017;83(11):e447-e449.
19. Angelos P. Can robotic approaches be justified for the benefit of surgeons? *Surgery (United States).* 2017;161(3):639-640.
20. Mitko J, Main W, Hussain L, Meister K, Kerlakian G, Tymitz K. Laparoscopic versus robotic cholecystectomy in the obese population: Is there a preferred approach? *Surgery for Obesity and Related Diseases.* 2016;12(7):S114-S115.
21. Eid JJ, Jyot A, Macedo FI, Sabir M, Mittal VK. Robotic Cholecystectomy Is a Safe Educational Alternative to Laparoscopic Cholecystectomy During General Surgical Training: A Pilot Study. *Journal of surgical education.* 2020.
22. Aggarwal R, Winter Beatty J, Kinross J, von Roon A, Darzi A, Purkayastha S. Initial Experience With a New Robotic Surgical System for Cholecystectomy. *Surgical innovation.* 2020;27(2):136-142.
23. Balachandran B, Hufford TA, Mustafa T, Kochar K, Sulo S, Khorsand J. A Comparative Study of Outcomes Between Single-Site Robotic and Multi-port Laparoscopic Cholecystectomy: An Experience from a Tertiary Care Center. *World journal of surgery.* 2017;41(5):1246-1253.
24. Chung PJ, Huang R, Policastro L, et al. Single-Site Robotic Cholecystectomy at an Inner-City Academic Center. *JSLS : Journal of the Society of Laparoendoscopic Surgeons.* 2015;19(3).
25. Hagen ME, Balaphas A, Podetta M, et al. Robotic single-site versus multiport laparoscopic cholecystectomy: a case-matched analysis of short- and long-term costs. *Surgical endoscopy.* 2018;32(3):1550-1555.
26. Lee EK, Park E, Oh WO, Shin NM. Comparison of the outcomes of robotic cholecystectomy and laparoscopic cholecystectomy. *Annals of surgical treatment and research.* 2017;93(1):27-34.
27. Lee SR, Kim HO, Shin JH. Clinical outcomes of single-incision robotic cholecystectomy versus conventional 3-port laparoscopic cholecystectomy. *Canadian journal of surgery Journal canadien de chirurgie.* 2019;62(1):52-56.
28. Li YP, Wang SN, Lee KT. Robotic versus conventional laparoscopic cholecystectomy: A comparative study of medical resource utilization and clinical outcomes. *The Kaohsiung journal of medical sciences.* 2017;33(4):201-206.
29. Wren SM, Curet MJ. Single-port robotic cholecystectomy: results from a first human use clinical study of the new da Vinci single-site surgical platform. *Archives of surgery (Chicago, Ill : 1960).* 2011;146(10):1122-1127.
30. Hagen ME, Balaphas A, Jung MK, Buchs NC, Buehler L, Morel P. Robotic single site versus multiport cholecystectomy: A case-matched analysis of short-and long-term costs. *Surgical Endoscopy and Other Interventional Techniques.* 2017;31:S53.
31. Teoh AY, Ng EK, Chan SM, Yip HC, Wong VW, Chiu PW. Endowrist equipped robotic laparoendoscopic single site access cholecystectomy versus 4 port laparoscopic cholecystectomy. A prospective comparative study. *Surgical Endoscopy and Other Interventional Techniques.* 2017;31:S328.
32. Abel SA, Al-Lami HS, Zeineddin S, Chandra A, Bingener-Casey J, Lyden ML. Robotic-Assisted Single Site Cholecystectomy and the Obese Patient: Single Center Outcomes Data. *Journal of the American College of Surgeons.* 2019;229(4):S112-S113.

33. Buzad FA, Corne LM, Brown TC, et al. Single-site robotic cholecystectomy: efficiency and cost analysis. *The international journal of medical robotics + computer assisted surgery : MRCAS.* 2013;9(3):365-370.
34. Gonzalez AM, Rabaza JR, Donkor C, Romero RJ, Kosanovic R, Verdeja JC. Single-incision cholecystectomy: a comparative study of standard laparoscopic, robotic, and SPIDER platforms. *Surgical endoscopy.* 2013;27(12):4524-4531.
35. Grochola LF, Soll C, Zehnder A, Wyss R, Herzog P, Breitenstein S. Robot-assisted single-site compared with laparoscopic single-incision cholecystectomy for benign gallbladder disease: results of a single-blinded randomized controlled trial. *HPB.* 2018;20:S726.
36. Gustafson M, Lescouflair T, Kimball R, Daoud I. A comparison of robotic single-incision and traditional single-incision laparoscopic cholecystectomy. *Surgical endoscopy.* 2016;30(6):2276-2280.
37. Spinoglio G, Lenti LM, Maglione V, et al. Single-site robotic cholecystectomy (SSRC) versus single-incision laparoscopic cholecystectomy (SILC): comparison of learning curves. First European experience. *Surgical endoscopy.* 2012;26(6):1648-1655.
38. Su WL, Huang JW, Wang SN, Lee KT. Comparison study of clinical outcomes between single-site robotic cholecystectomy and single incision laparoscopic cholecystectomy. *Asian journal of surgery.* 2017;40(6):424-428.
39. Autin RL, Singh TP, Binetti B. Incidence of port site hernia following single site laparoscopic and robotic cholecystectomy. *Surgical Endoscopy and Other Interventional Techniques.* 2015;29:S469.
40. Jang EJ, Roh YH, Kang CM, Kim DK, Park KJ. Single-Port Laparoscopic and Robotic Cholecystectomy in Obesity (>25 kg/m2). *JSLS : Journal of the Society of Laparoendoscopic Surgeons.* 2019;23(2).
41. Lee JH, Song KB, Shin SH, Kim SC, Lee YJ, Park KM. Robotic single-site cholecystectomy of 520 cases: Surgical outcomes and comparing with laparoscopic single-site procedure. *Surgical Endoscopy and Other Interventional Techniques.* 2018;32(1):S351.
42. Lescouflair T, Gustafson M, Daoud I. A comparison of robotic single incision and traditional single incision laparoscopic cholecystectomy. *Surgical Endoscopy and Other Interventional Techniques.* 2014;28:286.
43. Moore MD, Abelson J, Tholey R, Panjwani S, Zarnegar R, Afaneh C. Robotic single-incision cholecystectomy, although a feasible and safe option, dramatically increases operative time when compared to single-incision laparoscopic cholecystectomy. *Surgical Endoscopy and Other Interventional Techniques.* 2016;30:S494.
44. Aragon RJ, Lin C, Vidovszky TJ, Carr AD, Ali MR. Innovative approaches to laparoscopic cholecystectomy: A comparison of outcomes for single incision laparoscopic cholecystectomy, multi-port robotic cholecystectomy, and single site robotic cholecystectomy. *Surgical Endoscopy and Other Interventional Techniques.* 2014;28:437.
45. Altieri MS, Yang J, Telem DA, et al. Robotic approaches may offer benefit in colorectal procedures, more controversial in other areas: a review of 168,248 cases. *Surgical endoscopy.* 2016;30(3):925-933.
46. Farnsworth J, Surrusco M, Luo-Owen X, Yung E, Srikureja D, Mukherjee K. Is there a role for the robot in acute care surgery? *Journal of investigative medicine.* 2018;66(1):180-181.

47. Higgins RM, Frelich MJ, Bosler ME, Gould JC. Cost analysis of robotic versus laparoscopic general surgery procedures. *Surgical Endoscopy and Other Interventional Techniques.* 2016;30:S243.
48. Kitisin K, Packiam V, Celinski S, et al. Is the ever-expanding scope of robotics safe for hepatobiliary surgery too? *HPB.* 2011;13:33.
49. Khorgami Z, Li WT, Jackson TN, Howard CA, Sclabas GM. The cost of robotics: an analysis of the added costs of robotic-assisted versus laparoscopic surgery using the National Inpatient Sample. *Surgical endoscopy.* 2019;33(7):2217-2221.
50. Rosemurgy A, Ryan C, Klein R, Sukharamwala P, Wood T, Ross S. Does the cost of robotic cholecystectomy translate to a financial burden? *Surgical endoscopy.* 2015;29(8):2115-2120.
51. Strosberg DS, Nguyen MC, Muscarella P, 2nd, Narula VK. A retrospective comparison of robotic cholecystectomy versus laparoscopic cholecystectomy: operative outcomes and cost analysis. *Surgical endoscopy.* 2017;31(3):1436-1441.
52. Farukhi MA, Davis B. Robotic vs laparoscopic cholecystectomy: Which technique is optimal in morbidly obese patients? *Surgical Endoscopy and Other Interventional Techniques.* 2017;31:S327.
53. Ross S, Klein R, Ryan C, Toomey P, Sukharamwala P, Rosemurgy A. Does the cost of robotic cholecystectomy translate to a financial burden? *Surgical Endoscopy and Other Interventional Techniques.* 2014;28:247.
54. Strosberg DS, Nguyen MC, Muscarella IP, Narula VK. A retrospective comparison of robotic cholecystectomy versus laparoscopic cholecystectomy: Operative outcomes and cost analysis. *Surgical Endoscopy and Other Interventional Techniques.* 2016;30:S491.
55. Hawasli A, Sahly M, Meguid A, Edhayan E, Guiao C, Szpunar S. The impact of robotic cholecystectomy on private practice in a community teaching hospital. *American journal of surgery.* 2016;211(3):610-614.
56. Pokala B, Flores L, Armijo PR, Kothari V, Oleynikov D. Robot-assisted cholecystectomy is a safe but costly approach: A national database review. *American journal of surgery.* 2019;218(6):1213-1218.
57. Kane WJ, Charles EJ, Mehaffey JH, et al. Robotic compared with laparoscopic cholecystectomy: A propensity matched analysis. *Surgery.* 2020;167(2):432-435.
58. Kaminski JP, Bueltmann KW, Rudnicki M. Robotic versus laparoscopic cholecystectomy inpatient analysis: does the end justify the means? *Journal of gastrointestinal surgery : official journal of the Society for Surgery of the Alimentary Tract.* 2014;18(12):2116-2122.
59. Morris S, Patel N, Gurusamy K, Davidson B. Cost of robot versus human assistant in laparoscopic cholecystectomy. *HPB.* 2014;16:115.
60. Bedeir K, Mann A, Youssef Y. Robotic single-site versus laparoscopic cholecystectomy: Which is cheaper? A cost report and analysis. *Surgical endoscopy.* 2016;30(1):267-272.
61. Higgins RM, Frelich MJ, Bosler ME, Gould JC. Cost analysis of robotic versus laparoscopic general surgery procedures. *Surgical endoscopy.* 2017;31(1):185-192.
62. Newman RM, Umer A, Bozzuto BJ, Dilungo JL, Ellner S. Surgical Value of Elective Minimally Invasive Gallbladder Removal: A Cost Analysis of Traditional 4-Port vs Single-Incision and Robotically Assisted Cholecystectomy. *Journal of the American College of Surgeons.* 2016;222(3):303-308.

63. Prabhu AS, Carbonell A, Hope W, et al. Robotic Inguinal vs Transabdominal Laparoscopic Inguinal Hernia Repair: The RIVAL Randomized Clinical Trial. *JAMA surgery.* 2020.
64. Switzer N, Renshaw S, Holcomb C, et al. 6-month post-operative quality of life and pain comparisons between robotic and laparoscopic inguinal hernia repair. *Surgical Endoscopy.* 2019;33:S372.
65. Waite KE, Herman MA, Doyle PJ. Comparison of robotic versus laparoscopic transabdominal preperitoneal (TAPP) inguinal hernia repair. *Journal of robotic surgery.* 2016;10(3):239-244.
66. Kolachalam R, Dickens E, D'Amico L, et al. Early outcomes of robotic-assisted inguinal hernia repair in obese patients: a multi-institutional, retrospective study. *Surgical endoscopy.* 2018;32(1):229-235.
67. Kosturakis AK, LaRusso KE, Carroll ND, Nicholl MB. First 100 consecutive robotic inguinal hernia repairs at a Veterans Affairs hospital. *Journal of robotic surgery.* 2018;12(4):699-704.
68. Charles EJ, Mehaffey JH, Tache-Leon CA, Hallowell PT, Sawyer RG, Yang Z. Inguinal hernia repair: is there a benefit to using the robot? *Surgical Endoscopy.* 2018;32(4):2131-2136.
69. Gamagami R, Dickens E, Gonzalez A, et al. Open versus robotic-assisted transabdominal preperitoneal (R-TAPP) inguinal hernia repair: a multicenter matched analysis of clinical outcomes. *Hernia.* 2018;22(5):827-836.
70. Huerta S, Timmerman C, Argo M, et al. Open, Laparoscopic, and Robotic Inguinal Hernia Repair: Outcomes and Predictors of Complications. *Journal of Surgical Research.* 2019;241:119-127.
71. AlMarzooqi R, Tish S, Huang LC, Prabhu A, Rosen M. Review of inguinal hernia repair techniques within the Americas Hernia Society Quality Collaborative. *Hernia.* 2019;23(3):429-438.
72. Kakaishvili EK, Brauner EB, Kluger YK. Robotic inguinal hernia repair: Is it a new era in the surgical management of groin hernia? *Surgical Endoscopy.* 2018;32:S485.
73. Muysoms F, Van Cleven S, Kyle-Leinhase I, Ballecer C, Ramaswamy A. Robotic-assisted laparoscopic groin hernia repair: observational case-control study on the operative time during the learning curve. *Surgical Endoscopy.* 2018;32(12):4850-4859.
74. Kudsi OY, McCarty JC, Paluvoi N, Mabardy AS. Transition from Laparoscopic Totally Extraperitoneal Inguinal Hernia Repair to Robotic Transabdominal Preperitoneal Inguinal Hernia Repair: A Retrospective Review of a Single Surgeon's Experience. *World journal of surgery.* 2017;41(9):2251-2257.
75. Abdelmoaty WF, Dunst CM, Neighorn C, Swanstrom LL, Hammill CW. Robotic-assisted versus laparoscopic unilateral inguinal hernia repair: a comprehensive cost analysis. *Surgical endoscopy.* 2019;33(10):3436-3443.
76. Zayan NE, Meara MP, Schwartz JS, Narula VK. A direct comparison of robotic and laparoscopic hernia repair: patient-reported outcomes and cost analysis. *Hernia.* 2019.
77. Janjua H, Cousin-Peterson E, Barry TM, Kuo MC, Baker MS, Kuo PC. The paradox of the robotic approach to inguinal hernia repair in the inpatient setting. *American Journal of Surgery.* 2020;219(3):497-501.
78. Khoraki J, Gomez PP, Mazzini GS, et al. Perioperative outcomes and cost of robotic-assisted versus laparoscopic inguinal hernia repair. *Surgical Endoscopy.* 2019.

79. Sheldon RR, Do WS, Weiss JB, Forte DM, Sohn VY. Sage wisdom or anecdotal dictum? Equivalent opioid use after open, laparoscopic, and robotic inguinal hernia repair. *American journal of surgery.* 2019;217(5):839-842.
80. Knott LT, Shih IF, Song C, Paul Singh T. Comparison of robotic-assisted, laparoscopic and open surgery in primary inguinal hernia repair. *Surgical Endoscopy and Other Interventional Techniques.* 2018;32(1):S46.
81. Macias AE, Jacome F, Punshon J. Inguinodynia-tastic: A comparison between robotic and laparoscopic inguinal hernia repair. *Journal of the American College of Surgeons.* 2017;225(4):e88.
82. Pokala B, Armijo PR, Flores L, Hennings D, Oleynikov D. Minimally invasive inguinal hernia repair is superior to open: a national database review. *Hernia.* 2019;23(3):593-599.
83. Lammers DT, Kuckelman JP, Bingham J. *51.03 Comparison of Robotic Versus Laparoscopic and Open Repair for Inguinal Hernias.* Madigan Army Medical Center, Department Of General Surgery2019.
84. Holcomb CN, Huang LC, Renshaw S, et al. Wound complications after inguinal hernia repair, has robotic surgery improved outcomes? *Surgical Endoscopy.* 2019;33:S362.
85. Abdalla R, Santo M, Gontijo C, Frade Said D, Cecconello I, Costa T. Randomized clinical trial: camparison between robotic assited and laparoscopic incisional hernia repair. *Hernia.* 2017;21(1):S115-.
86. Bittner JGt, Alrefai S, Vy M, Mabe M, Del Prado PAR, Clingempeel NL. Comparative analysis of open and robotic transversus abdominis release for ventral hernia repair. *Surgical endoscopy.* 2018;32(2):727-734.
87. Martin-Del-Campo LA, Weltz AS, Belyansky I, Novitsky YW. Comparative analysis of perioperative outcomes of robotic versus open transversus abdominis release. *Surgical endoscopy.* 2018;32(2):840-845.
88. Nguyen B, David B, Gosch K, Sorensen GB. Comparisons of abdominal wall reconstruction for ventral hernia repairs, open versus robotic. *Surgical Endoscopy.* 2019;33:S354.
89. Switzer N, Renshaw S, Holcomb C, et al. Evaluating abdominal wall function post ventral hernia repair: A comparison of open versus robotic-assisted retromuscular techniques. An americas hernia society quality collaborative study. *Surgical Endoscopy.* 2019;33:S362.
90. Carbonell AM, Warren JA, Prabhu AS, et al. Reducing Length of Stay Using a Robotic-assisted Approach for Retromuscular Ventral Hernia Repair: A Comparative Analysis From the Americas Hernia Society Quality Collaborative. *Annals of surgery.* 2018;267(2):210-217.
91. A. Guzman-Pruneda F, Huang LC, Collins C, Renshaw S, Narula V, B KP. Abdominal core quality of life after ventral hernia repair: a comparison of open versus robotic-assisted retromuscular techniques. *Surgical Endoscopy.* 2020.
92. Roberts SH, Rodman CP, Meara MP. Short-Term Outcomes of Robotic vs Open Transversus Abdominus Release. *Journal of the American College of Surgeons.* 2019;229(4):e128.
93. Lu R, Addo A, Ewart Z, et al. Comparative review of outcomes: laparoscopic and robotic enhanced-view totally extraperitoneal (eTEP) access retrorectus repairs. *Surgical Endoscopy.* 2019.

94. Khorgami Z, Li WT, Jackson TN, Howard CA, Sclabas GM. The cost of robotics: an analysis of the added costs of robotic-assisted versus laparoscopic surgery using the National Inpatient Sample. *Surgical Endoscopy.* 2019;33(7):2217-2221.
95. Gonzalez AM, Romero RJ, Seetharamaiah R, Gallas M, Lamoureux J, Rabaza JR. Laparoscopic ventral hernia repair with primary closure versus no primary closure of the defect: potential benefits of the robotic technology. *The international journal of medical robotics + computer assisted surgery : MRCAS.* 2015;11(2):120-125.
96. Prabhu AS, Dickens EO, Copper CM, et al. Laparoscopic vs Robotic Intraperitoneal Mesh Repair for Incisional Hernia: An Americas Hernia Society Quality Collaborative Analysis. *Journal of the American College of Surgeons.* 2017;225(2):285-293.
97. Walker PA, May AC, Mo J, et al. Multicenter review of robotic versus laparoscopic ventral hernia repair: is there a role for robotics? *Surgical Endoscopy.* 2018;32(4):1901-1905.
98. Coakley KM, Sims SM, Prasad T, et al. A nationwide evaluation of robotic ventral hernia surgery. *American journal of surgery.* 2017;214(6):1158-1163.
99. Altieri MS, Yang J, Xu J, Talamini M, Pryor A, Telem DA. Outcomes after Robotic Ventral Hernia Repair: A Study of 21,565 Patients in the State of New York. *The American surgeon.* 2018;84(6):902-908.
100. Chen YJ, Huynh D, Nguyen S, Chin E, Divino C, Zhang L. Outcomes of robot-assisted versus laparoscopic repair of small-sized ventral hernias. *Surgical endoscopy.* 2017;31(3):1275-1279.
101. Warren JA, Cobb WS, Ewing JA, Carbonell AM. Standard laparoscopic versus robotic retromuscular ventral hernia repair. *Surgical endoscopy.* 2017;31(1):324-332.
102. Mudyanadzo TA, Hunter JD, Rider PF, Richards WO. An Evaluation of Robotic Ventral Hernia Repair. *The American surgeon.* 2020;86(1):e45-e46.
103. Song C, Liu E, Shi L, Marcus D. Comparative effectiveness for ventral hernia repairs among an obese patient population. *Surgical Endoscopy and Other Interventional Techniques.* 2017;31:S136.
104. Armijo P, Pratap A, Wang Y, Shostrom V, Oleynikov D. Robotic ventral hernia repair is not superior to laparoscopic: a national database review. *Surgical Endoscopy.* 2018;32(4):1834-1839.
105. Makra GM, Dechantsreiter G, Holzapfel K. *ROFO Fortschr Geb Rontgenstr Nuklearmed.* 2019;191(1):67-69.
106. Hagen ME, Jung MK, Fakhro J, et al. Robotic versus laparoscopic stapling during robotic Roux-en-Y gastric bypass surgery: a case-matched analysis of costs and clinical outcomes. *Surgical endoscopy.* 2018;32(1):472-477.
107. Tan WH, McAllister J, Feaman S, Blatnik JA. Cost comparison of laparoscopic versus robotic ventral hernia repairs. *Surgical Endoscopy and Other Interventional Techniques.* 2018;32(1):S18.
108. Lim JH, Lee WJ, Park DW, Yea HJ, Kim SH, Kang CM. Robotic cholecystectomy using Revo-i Model MSR-5000, the newly developed Korean robotic surgical system: a preclinical study. *Surgical endoscopy.* 2017;31(8):3391-3397.
109. Tom CM, Maciel JD, Korn A, et al. A survey of robotic surgery training curricula in general surgery residency programs: How close are we to a standardized curriculum? *American journal of surgery.* 2019;217(2):256-260.
110. George LC, O'Neill R, Merchant AM. Residency Training in Robotic General Surgery: A Survey of Program Directors. *Minim Invasive Surg.* 2018;2018:8464298.

111. Carpenter BT, Sundaram CP. Training the next generation of surgeons in robotic surgery. *Robot Surg.* 2017;4:39-44.
112. Wee IJY, Kuo LJ, Ngu JC. A systematic review of the true benefit of robotic surgery: Ergonomics. *The international journal of medical robotics + computer assisted surgery : MRCAS.* 2020:e2113.
113. Lee GI, Lee MR, Green I, Allaf M, Marohn MR. Surgeons' physical discomfort and symptoms during robotic surgery: a comprehensive ergonomic survey study. *Surgical endoscopy.* 2017;31(4):1697-1706.
114. Dwyer A, Huckleby J, Kabbani M, Delano A, De Sutter M, Crawford D. Ergonomic assessment of robotic general surgeons: a pilot study. *Journal of robotic surgery.* 2020;14(3):387-392.
115. Patel SV, Yu D, Elsolh B, Goldacre BM, Nash GM. Assessment of Conflicts of Interest in Robotic Surgical Studies: Validating Author's Declarations With the Open Payments Database. *Annals of surgery.* 2018;268(1):86-92.
116. Calatayud D, Kakarla VR, Coratti F, et al. Minimally invasive cholecystectomy-retrospective study comparing laparoscopic vs robotic approach. *Surgical Endoscopy and Other Interventional Techniques.* 2012;26:S413.

APPENDIX A. SEARCH STRATEGIES

CHOLECYSTECTOMY

DATABASE SEARCHED & TIME PERIOD COVERED:
Pubmed – 2010-2020

"Robotic Surgical Procedures"[Mesh] OR robotics[mh] OR robot-assisted OR robot*[tiab] OR robot*[ot]
AND
cholecystectomy[tiab]OR cholecystectomies[tiab])) OR cholecystectomy[MeSH]
AND
"2010"[Date - Publication] : 2020[Date - Publication]

DATABASE SEARCHED & TIME PERIOD COVERED:
EMBASE – 2010-2020

'robot assisted surgery'/exp OR 'robot assisted surgery' OR 'robot assisted' OR robot*
AND
Cholecystectomy/exp OR Cholecystectomy OR Cholecystectomies
AND
Publication years 2010-2020

DATABASE SEARCHED & TIME PERIOD COVERED:
Cochrane 2010-2020

Robotic assisted surgical procedures OR robotics OR (MESH descriptor)Robotic Surgical Procedures/exp OR (MESH descriptor)Robotics/exp
AND
(MESH Descriptor)Cholecystectomy/exp OR (Cholecystectomy OR Cholecystectomies)ti,ab,kw
AND
Publication years Jan 2010-Dec 2020

INGUINAL HERNIA

DATABASE SEARCHED & TIME PERIOD COVERED:
PUBMED – 2010-2020

"Robotic Surgical Procedures"[Mesh] OR robotics[mh] OR robot-assisted OR robot*[tiab] OR robot*[ot]
OR
surgical mesh or open surgical technique* or open operative technique* or open suture repair* or mesh repair*
OR
"Abdominal Wall/surgery"[Mesh] OR "Hernia, Ventral/surgery"[Mesh]

AND

Hernia, Inguinal[MESH] OR “inguinal hernia” OR “inguinal hernias” OR Groin[MESH] OR Groin or groins

AND
(limit) Humans
AND
(limit) adult
AND

"2010"[Date - Publication] : "2020"[Date - Publication]

DATABASE SEARCHED & TIME PERIOD COVERED:
EMBASE – 2010 - 2020

'robot assisted surgery'/exp OR 'robot assisted surgery' OR 'robot assisted' OR robot*
AND
‘inguinal hernia/exp OR inguinal region/exp OR “inguinal hernia” OR “inguinal hernias” OR groin OR groins
AND
Human/de
AND
adult/lim OR aged/lim OR very elderly/lim
AND
Publication years 2010-2020

DATABASE SEARCHED & TIME PERIOD COVERED:
COCHRANE Reviews – 2010- Dec 2020

Robotic assisted surgical procedures OR robotics OR (MESH descriptor) Robotic Surgical Procedures/exp OR (MESH descriptor)Robotics/exp

AND

1. explode inguinal hernia (MeSH)
2. inguinal herni* ti,ab,kw
3. shouldice. ti,ab,kw
4. bassini. ti,ab,kw
5. mcvay. ti,ab,kw
6. stoppa.t ti,ab,kw
7. (laparoscop* NEAR25 herni*) ti,ab,kw
8. (tension-free NEAR25 herni*) ti,ab,kw
9. (conventional NEAR25 herni*). ti,ab,kw
10. (open NEAR25 herni*). ti,ab,kw
11. (darn NEAR25 herni*). ti,ab,kw
12. (mesh NEAR25 hern*). ti,ab,kw
13. (traditional NEAR25 herni*) ti,ab,kw
14. (plug NEAR25 herni*).t ti,ab,kw

15.(lichtenstein NEAR25 herni*).tw
16. 1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9 or 10 or 11 or 12 or 13 or 14 or 15

AND

Publication years Jan 2010- Dec2020

Notes on ENL:
Created separate ENL for Cochrane which was deduped and then copied into other ENL
keyword: child, manually reviewed and deleted records

DATABASE SEARCHED & TIME PERIOD COVERED:
OVID MEDLINE & Epub Ahead of Print, In-Process & Other Non-Indexed Citations and Daily - 1946 to March 26, 2020)

1. exp Hernia, Ventral/su [Surgery]
2. Abdominal Wall/su [Surgery]
3. (surgical mesh or open surgical technique* or open operative technique* or open suture repair* or mesh repair*).mp. [mp=title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]
4. 1 or 2 or 3
5. Hernia/
6. exp Hernia, Inguinal
7. Groin/
8. inguinal hernia or inguinal hernias or groin or groins
9. 5 or 6 or 7 or 8
10. 4 and 9

Limit – humans, 2010-2020, young adult, adult, middle age, middle aged, all aged

<u>VENTRAL HERNIA</u>

DATABASE SEARCHED & TIME PERIOD COVERED:
PUBMED – 2010-2020

"Robotic Surgical Procedures"[Mesh] OR robotics[mh] OR robot-assisted OR robot*[tiab] OR robot*[ot]
AND
“surgical mesh” or “open surgical technique*” or “open operative technique*” or “open suture repair*” or “mesh repair*”
OR
"Abdominal Wall/surgery"[Mesh] OR "Hernia, Ventral/surgery"[Mesh]

AND

"ventral hernia" OR "incisional hernia"
OR
ventral hernia or incisional hernia
OR
"Hernia"[Mesh])
OR
“Hernia, Ventral"[Mesh]

AND
(limit) Humans
AND
(limit) adult
AND
"2010"[Date - Publication] : "3000"[Date - Publication]

DATABASE SEARCHED & TIME PERIOD COVERED:
EMBASE - 2010-2020

'robot assisted surgery'/exp OR 'robot assisted surgery' OR 'robot assisted' OR robot*
AND
Abdominal wall hernia/exp OR incisional hernia/exp OR umbilical hernia/exp OR epigastric hernia/exp OR 'incisional hernia' OR 'incisional hernias' OR 'ventral hernia' OR 'ventral hernias' OR 'umbilical hernia' OR 'umbilical hernias' OR 'epigastric hernia' OR 'epigastric hernias'
AND
Human/de
AND
adult/lim OR aged/lim OR very elderly/lim
AND
Publication years 2010-2020

DATABASE SEARCHED & TIME PERIOD COVERED:
COCHRANE – Jan 2010 – Dec 2020

Robotic assisted surgical procedures OR robotics OR (MESH descriptor) Robotic Surgical Procedures/exp OR (MESH descriptor)Robotics/exp
AND
Incisional hernia(Mesh descriptor)/exp OR Hernia, ventral(Mesh descriptor)/exp OR Hernia, umbilical (Mesh descriptor)/exp OR “incisional hernia” OR “Incisional hernias” OR “ventral hernia” OR “ventral hernias” OR “umbilical hernia” OR “umbilical hernias” OR “epigastric hernia” OR “epigastric hernias”:ti,ab,kw
AND
Publication years Jan 2010- Dec2020
NB: results reviewed for animal and children exclusion

DATABASE SEARCHED & TIME PERIOD COVERED:
OVID MEDLINE & Epub Ahead of Print, In-Process & Other Non-Indexed Citations and Daily (1946 to March 26, 2020) –

1. exp Hernia, Ventral/su [Surgery]
2. Abdominal Wall/su [Surgery]
3. (surgical mesh or open surgical technique* or open operative technique* or open suture repair* or mesh repair*).mp. [mp=title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]
4. 1 or 2 or 3
5. Hernia/
6. exp Hernia, Ventral/

(ventral hernia or incisional hernia).mp. [mp=title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]

8. 5 or 6 or 7
9. 4 AND 8

AND
Humans (limit)
AND
Young adult OR adult Or middle age OR middle aged or all aged OR aged (limit)
AND
2010-1091 (limit)

APPENDIX B. PEER REVIEWER COMMENTS AND RESPONSES

Reviewer comment	Authors Responses
	Note to the reviewers, we updated our search through April 2020. This added a handful of studies (5 cholecystectomy; 4 inguinal hernia repair; 4 ventral hernia repair). 1 inguinal study is an RCT. These did not change our main conclusions.
Yes - Throughout this very well written manuscript there is a biased assumption that the capabilities of surgeons operating laparoscopically and robotically are similar. This would be the majority view but I strongly believe that it is incorrect. Robotic instruments and integrated real 3 dimensional vision generated by 2 cameras, 1 for each eye is vastly different than laparoscopy. Could robotic procedures be longer because surgeons are seeing better and working safer? Could robotic procedures take longer because more complex cases are being performed? Are robotic procedures taking longer because the staff are less experienced? Where are robotic surgeons in their learning curves within all of these studies? Laparoscopy has been main stream for more than 30 years so the experience of surgeons with laparoscopy would have to be significantly higher.	Yes. We agree that the robot offers clear advantages and have added comments about these to the Discussion. Thanks for your other comments. We expanded our Discussion section on: increased OR time/ safer; complexity of cases; learning curves.
Yes - As the authors know, the topic of robotic use in General Surgery is a very fluid and hot topic. Because the literature is continually changing with new studies, albeit, not RCTs, it is really difficult to make definitive conclusions. There was a recent study in the last 6 months comparing robotic and laparoscopic ventral hernia repair and concluded no difference in outcomes studied. The outcome that is not typically included in most studies is postoperative pain for all 3 procedures. Many experts feel the major benefit of robotic repair of both incisional and inguinal hernias is the avoidance of using tacks. The ability to use intra-corporal sewing with the robot for securing mesh with ventral hernias and avoiding tacks does reduce postop pain. Similarly, the use of mesh that eliminates the need for sutures for robotic inguinal hernia repair definitely reduces acute and chronic pain for these patients. So perhaps comments in these 2 areas would be helpful for the reader. I agree with the authors that it is really hard to justify by any outcome that there is a benefit to using a robot for cholecystectomy.	Yes. Thank you for your suggestion. We added comments to our Discussion about 1) benefit of robotic approach for hernia repairs as tacks aren't used; 2) sutureless mesh. Thank you for this comment. We are working several manuscripts to submit.

Compliments to the authors for an excellent review. Suggest you convert this into a manuscript that could be published in a surgical journal.	
Edits recommended as below: Page 4, Lines 32-40: Degrees/titles edited; recommend deletion of mailstops (10NC2) Mark A. Wilson, MD, PhD National Director of Surgery (10NC2) Department of Veterans Affairs William Gunnar, MD Executive Director, National Center for Patient Safety Former National Director of Surgery (10NC2) Department of Veterans Affairs	Thank you for your edits. These corrections were made.
Page 6, Lines 25-44: Capitalization is not consistent. Standardize terminology to robot-assisted for all uses. RESULTS .... 19 Key Question 1A – Cholecystectomy: What is the clinical effectiveness of robot-assisted surgery compared to conventional laparoscopic surgery for cholecystectomy?...................... 23 Key Question 2A – cholecystectomy: what is the cost-effectiveness of robot-assisted surgery compared to conventional laparoscopic surgery for cholecystectomy? .... 30 Key Question 1B – inguinal hernia surgery: What is the clinical effectiveness of robot-assisted surgery compared to conventional laparoscopic or open surgery for inguinal hernia repair? 38 Key Question 2B – Inguinal Hernia Surgery: what is the cost-effectiveness of robotic-assisted surgery compared to conventional laparoscopic OR open surgery for inguinal hernia repair? .... 47 Key Question 1C – VentraL hernia surgery: What is the clinical effectiveness of robotic assisted surgery compared to conventional laparoscopic or open surgery for ventral hernia repair?... 49 Key Question 2C – Ventral Hernia Surgery: what is the cost-effectiveness of robot-assisted surgery compared to conventional laparoscopic OR open surgery for ventral hernia repair? 59	These corrections were made.

Page 8, Lines 39-33: Delete mailstops (10NC2); add current title for Dr. Gunnar as below: This topic was developed in response to a nomination by Dr. Mark Wilson, National Director of Surgery (10NC2), and Dr. William Gunnar, Executive Director, National Center for Patient Safety and former National Director of Surgery (10NC2). Key questions were then developed with input from the topic nominator, the ESP coordinating center, the review team, and the technical expert panel (TEP).	
Very nice review. I have a couple minor edits/suggestions. Page 7, line 42 would add ….We assessed robotic and laparoscopic approach for cholecystectomy, as open cholecystectomy is typically performed for cancer pathology or in the setting of significant inflammation or adhesive disease. page 7 line 49 ,...in order (to) lessen confounding factors page 8 line 20. not sure what is meant by "technique factors".... page 41 line 11 - I think there are extra tick marks for length of stay. I suspect that the learning curve of robotic general surgery played a large part in increased operative times. Most of the studies compared early surgeon experience with the robot compared with years of experience laparoscopically. Perhaps a reference about learning curve and robotic surgery could be included. Inguinal hernia repairs and cholecystectomies rarely require inpatient hospitalization. This should be noted.	Requested edits were made to pages 7-8. For page 41 comment: These studies reported inpatient and outpatient LOS so both were listed. We now display only outpatient values which generalizes better to how most are done. We added a clarification that inguinal hernias and cholecystectomy are mainly outpatient procedures.
Robotic surgery is an exciting field with more advanced procedures being performed daily. Although the technology has been available for years there is still a learning curve for the surgeon and may be reflected by longer case times initially. As it becomes more integrated into practice I foresee the benefits will rise. This review is a great resource for those interested in robotic general surgery and how it compares to laparoscopic and open surgery. The authors skillfully reviewed many studies and have	Thanks for the comments. We added to the Discussion more specifics about the potential learning curve. It is possible that more complex gallbladder cases are preferentially done with the robot, but this was hard to assess with the studies as case complexity wasn't defined well for the benign disease. RCTs for cholecystectomy should control reasonably well for this potential difference. We also added comments

put together a comprehensive overview of the data we have thus far. Thank you for acknowledging the limitations of all these heterogenous studies. Page numbers based on pdf document, not those printed on the text. Cholecystectomy: Did the studies look at difficulty of gallbladder surgery? *Ie* were the robotic gallbladders done because of an expected difficult surgery vs laparoscopic technique? This is alluded to further in the discussion as a selection bias. Inguinal hernias: Pg 11: Again was the difficulty of the hernias looked at in the demographics and case matching? I would always choose a robotic repair over laparoscopic if expected to be difficult (patient obesity, size of hernia defect, incarceration, bowel involvement). Since the cost effectiveness sections all came to the same conclusions perhaps they could be condensed into 1 section. Discussion: Differences in OR time across studies is possibly due to docking time of the robot but an efficient team can do this in 10 minutes or less. I would also be careful placing a lot of weight on the differences in OR time especially if not a great time difference between technique. Faster is not necessarily better for the patient. I think a lot of the difference is due to the learning curve with starting robotic surgeries, the efficiency of the OR team and mostly the difficulty of the case. When choosing a surgical technique for hernia or gallbladder I always consider the robot when I anticipate a case to be more difficult. *Ie* larger hernia, incarcerated bowel, recurrence hernia, chronic cholecystitis with PCT. These cases will always take me longer because of the difficulty not because of the robot. The LOS is a hard measure to compare as most of these cases are done outpatient regardless of technique. Again I don't think there is a big clinical impact here but all the studies mention it. As for the cost I agree that no conclusions can be made based on the evidence. These sections could be condensed into 1 for cholecystectomy and hernias. Does the VA have any cost data to look at internally? "Urologic surgery has been widely adopted in the VA, so this experience for the staff may translate into an easy implementation to	about use of robot for more complex cases including cancer in the Discussion. We added more cost data and have chosen to present them by the individual procedures. Cost range is quite different between these groups so it seems better to keep them separate. Differences between study arms for hernias were multi-factorial. Sometimes matching was on patient factors, but not for hernia size or complexity. And sometimes visa versa. Standardized matching across studies on the most pertinent factors would be very useful. Studies typically matched based on the available variables available in their dataset. This comment was added to our Discussion as well. We added comments to address your points – gallbladder difficulty was poorly assessed for observational studies. Yes. The difficulty of cases for inguinal hernias was also hard to assess. Particularly for inguinal hernias, there were gaps in reported information to assess. We did our best to control for laterality (unilateral, bilateral) as this would greatly impact outcomes we were interested in. Unfortunately, we are not aware of any cost data within the VA. We are in the process of accessing VA utilization data on robotic surgery. A comment on this was added to the Discussion section.

the robotic general surgery field." I agree with this statement. Most OR staff is familiar with robotic surgery and adept at use. Research Gaps: Agree with surgeon learning curve affecting outcomes of studies. Additionally the difficulty of cases effects outcomes. Agree with need for long term follow up to prove hernia recurrence is lower or higher for each technique. Cholecystectomy for cancer should be considered on its own for clinical effectiveness. This operation may involve a partial hepatectomy depending on pathology. Additionally studies need to clearly compare cases based on the difficulty as I mentioned earlier. A small ventral hernia with no adhesions or bowel involvement can be done in 1-2 hours, whereas a larger ventral hernia with need for adhesiolysis and component release will take 3-5 hours. Surgeon experience is a critical component in deciding which technique to use. At the end of the day the best operation for the patient is the 1 the surgeon is most experienced with. I do not foresee many RRT being done for robotic vs laparoscopic vs open surgery in the future. The robotic surgery platform is taking off and has been proving itself without these trials.	
This is an exhaustive review and is balanced well with the exception of the bias that I perceive as described above. It is clear that the authors have worked very dilligently to use language that avoids this bias against robotics but I would consider adding a section related to the expanded capabilities that robotic surgery has offered. For example lap inguinal hernias nation wide never exceeded 20% of total cases. However, with the addition of robotically trained inguinal hernia surgeons large markets, not just individual surgeons, now are able to offer minimally invasive inguinal hernia surgery to greater than 40% of an entire market. Personally, I saw my busy inguinal practice go from 60%mis 40%open to 95%MIS vs 5%open with the addition of the robotic platform to my armamentarium of procedures that I may thoughtfully offer to patients. The end result is that more patients are able to have an MIS hernia repair and this increased cost is worth it to each patient that has shorter times of lifting restrictions, less opioid utilization, earlier return to full activity, and earlier return to work.	Thanks for the comment. We added text about the expanded capabilities of robotic surgery to the Discussion section. We added to the Discussion the importance of balancing added cost with potential benefits to the patient.

The authors should be commended for synthesizing a large amount of data that stems from very disparate data sources with variable methodologies and end points. The authors appropriately used the GRADE methodology to rate the quality of the evidence. They also appropriately noted that data was too heterogenous to allow for meta-analysis and instead presented this as a systematic narrative review of the evidence. The authors clearly delineated their search strategy and analytic framework. They also note limitations in the study, including the learning curve effect of robotic surgery as the newer technology which may predispose towards higher costs and longer operative times for the newer procedures. The authors do address risk of bias in the published data but primarily discuss this in terms of publication bias and not selection or author bias. There is excellent literature that suggests that there is significant bias in published reports of robotic surgery, and specifically that studies with unreported Conflict of Interest are significantly more favorable towards robotics (example: https://www.ncbi.nlm.nih.gov/pubmed/28700443) The data seems clear that robotic surgery takes longer. There are some limited indications that a few selected patient outcome metrics are improved with robotics compared to open surgery and that conversion to open surgery may be less often needed in robotics compared to laparoscopy. There is 1 area were robotic surgery seems to be have clinically worse outcomes, notably single port robotic surgery leading to higher incisional hernia rates compared to multiple port laparoscopy. Because the studies were selected as RCTs or case comparisons, the data sources are unable to answer an important question of whether robotics allows some cases to be done via a minimally invasive approach as opposed to an open approach. Robotic advocates often claim that the robot allows some procedures to be done minimally invasively instead of open, but some market data in hernia surgery suggests that more cases seem to be converting from laparoscopic to robotic, as opposed to open cases transitioning to robotic. Studies looking at market adoption of robotic surgery could help answer this question, but would require an additional avenue of analysis. Costs seem to be higher in robotics, but due to limitations in data and methodology this is less certain, and likely varies depending on the particulars of an operation and the method of accounting. For example, the costs of robotic acquisition are	Excellent point, we have added a sentence about the evolution of the robotic platform to other companies and types of technology. Thank you for your comment. We have added these additional gaps in the Discussion. We added several additional research gaps to the Discussion, including the ones listed here: surgeon ergonomics, surgical education, learning curve, and anticipated new robotic platforms.

handled variably across studies, as is the cost of length of stay data.

The authors use their systematic review to identify 4 areas with a research gap as a guide to future research. These areas are well considered and are all worthy of future study. Because the literature review focused on patient outcomes and cost, the identified research gaps are obviously focused on these areas. There are several major research gaps not identified in this review as they do not directly arise in the types of studies considered in this analysis:
1) Surgeon ergonomics and workload. Surgeons have a very high rate of musculoskeletal disorders due to the ergonomic challenges of both open and laparoscopic surgery. Advocates for robotic surgery often allege that ergonomics are improved and surgeon stress/workload/fatigue is decreased with robotic adoption, and postulate that this will result in improved surgeon longevity. Although data in this area is sparse, it would be a valuable additional area for future research.
2) Surgical education and learning curve. Robotics is a new and evolving technology. This is creating major issues in surgical education - both in education of surgical trainees and also in education of surgeons in practice who are learning new approaches. The advent of laparoscopy more than 20 years ago showed the importance of education and learning curves, as patient injury rates skyrocketed during the early years of laparoscopic surgery.
3) Future innovation in surgical robotics. Although not discussed in the review, all of the studies addressed here are using the da Vinci system from Intuitive. There are several new robotic platforms that will soon be available, and these will come with new opportunities and challenges with regard to technical issues, patient outcomes, and costs. Additionally, robotic platforms offer the potential for new advances in computer vision, machine learning, and automation that may transform the surgical landscape. These are areas rife with research opportunities.

APPENDIX C. COCHRANE RISK OF BIAS TOOL

The Cochrane Collaboration's Tool for Assessing Risk of Bias*

Domain	Support for judgement	Review authors' judgement
Selection bias.		
Random sequence generation.	Describe the method used to generate the allocation sequence in sufficient detail to allow an assessment of whether it should produce comparable groups.	Selection bias (biased allocation to interventions) due to inadequate generation of a randomised sequence.
Allocation concealment.	Describe the method used to conceal the allocation sequence in sufficient detail to determine whether intervention allocations could have been foreseen in advance of, or during, enrolment.	Selection bias (biased allocation to interventions) due to inadequate concealment of allocations prior to assignment.
Performance bias.		
Blinding of participants and personnel *Assessments should be made for each main outcome (or class of outcomes).*	Describe all measures used, if any, to blind study participants and personnel from knowledge of which intervention a participant received. Provide any information relating to whether the intended blinding was effective.	Performance bias due to knowledge of the allocated interventions by participants and personnel during the study.
Detection bias.		
Blinding of outcome assessment *Assessments should be made for each main outcome (or class of outcomes).*	Describe all measures used, if any, to blind outcome assessors from knowledge of which intervention a participant received. Provide any information relating to whether the intended blinding was effective.	Detection bias due to knowledge of the allocated interventions by outcome assessors.
Attrition bias.		
Incomplete outcome data *Assessments should be made for each main outcome (or class of outcomes).*	Describe the completeness of outcome data for each main outcome, including attrition and exclusions from the analysis. State whether attrition and exclusions were reported, the numbers in each intervention group (compared with total randomized participants), reasons for attrition/exclusions where reported, and any re-inclusions in analyses performed by the review authors.	Attrition bias due to amount, nature or handling of incomplete outcome data.
Reporting bias.		
Selective reporting.	State how the possibility of selective outcome reporting was examined by the review authors, and what was found.	Reporting bias due to selective outcome reporting.
Other bias.		
Other sources of bias.	State any important concerns about bias not addressed in the other domains in the tool. If particular questions/entries were pre-specified in the review's protocol, responses should be provided for each question/entry.	Bias due to problems not covered elsewhere in the table.

* http://handbook.cochrane.org/ in Table 8.5.a

APPENDIX D. RISK OF BIAS IN NON-RANDOMISED STUDIES – OF INTERVENTIONS (ROBINS-I)

Bias domains included in ROBINS-I[10]

Pre-intervention	Risk of bias assessment is mainly distinct from assessments of randomised trials
Bias due to confounding	Baseline confounding occurs when 1 or more prognostic variables (factors that predict the outcome of interest) also predicts the intervention received at baseline ROBINS-I can also address time-varying confounding, which occurs when individuals switch between the interventions being compared and when post-baseline prognostic factors affect the intervention received after baseline
Bias in selection of participants into the study	When exclusion of some eligible participants, or the initial follow-up time of some participants, or some outcome events is related to both intervention and outcome, there will be an association between interventions and outcome even if the effects of the interventions are identical This form of selection bias is distinct from confounding—A specific example is bias due to the inclusion of prevalent users, rather than new users, of an intervention
At intervention	Risk of bias assessment is mainly distinct from assessments of randomised trials
Bias in classification of interventions	Bias introduced by either differential or non-differential misclassification of intervention status Non-differential misclassification is unrelated to the outcome and will usually bias the estimated effect of intervention towards the null Differential misclassification occurs when misclassification of intervention status is related to the outcome or the risk of the outcome, and is likely to lead to bias
Post-intervention	Risk of bias assessment has substantial overlap with assessments of randomised trials
Bias due to deviations from intended interventions	Bias that arises when there are systematic differences between experimental intervention and comparator groups in the care provided, which represent a deviation from the intended intervention(s) Assessment of bias in this domain will depend on the type of effect of interest (either the effect of assignment to intervention or the effect of starting and adhering to intervention).
Bias due to missing data	Bias that arises when later follow-up is missing for individuals initially included and followed (such as differential loss to follow-up that is affected by prognostic factors); bias due to exclusion of individuals with missing information about intervention status or other variables such as confounders
Bias in measurement of outcomes	Bias introduced by either differential or non-differential errors in measurement of outcome data. Such bias can arise when outcome assessors are aware of intervention status, if different methods are used to assess outcomes in different intervention groups, or if measurement errors are related to intervention status or effects
Bias in selection of the reported result	Selective reporting of results in a way that depends on the findings and prevents the estimate from being included in a meta-analysis (or other synthesis)

APPENDIX E. QUALITY ASSESSMENT FOR INCLUDED RCT STUDIES

CHOLECYSTECTOMY

Author, year	Random sequence generation	Allocation concealment	Blinding of participants and personnel	Blinding of outcome assessment	Incomplete outcome data	Selective reporting	Other sources of bias
Grochola, 2019[13] Intraop	○	◒	●	◒	○	○	○
Patient measures	○	◒	○	○	○	○	○
Heemskerk, 2014[14]	◒	◒	◒	◒	○	○	●
Kudsi, 2017[15]	○	○	◒	●	○	○	○
Pietrabissa, 2016[16]	○	○	○	○	○	○	○

○= low risk of bias ● = risk of bias ◒ = unknown

INGUINAL HERNIA REPAIR

Author, year	Random sequence generation	Allocation concealment	Blinding of participants and personnel	Blinding of outcome assessment	Incomplete outcome data	Selective reporting	Other sources of bias
Prabhu 2020[63]	○	◒	● Single-blinded	◒	○	○	● Intuitive funded institutional research grant to 1st author; 6 authors received honoraria from Intuitive (including 1st author)

○ = low risk of bias ● = risk of bias ◒ = unknown

APPENDIX F. QUALITY ASSESSMENT FOR INCLUDED OBSERVATIONAL STUDIES

CHOLECYSTECTOMY

Author, year	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 the reported result	Other source of bias
Abel, 2019[32]	Serious: not discussed	Serious: unknown how offered	Low	Low	No information	Low	Low	n/a
Aggarwal, 2020[22]	Low: no serious demographic differences	Low: surgical method based on scheduled surgery date	Low	Low	Low (short follow-up)	Low	Low	n/a
Albrecht, 2017[17]	Low: matched	Moderate: unknown how offered	Low	Low	No information	Moderate: patient-reported pain scores	Low	n/a
Altieri, 2016[45]	Low: propensity matching	Serious: unknown how offered, database	Low	Low	No information	Low	Low	n/a
Aragon, 2014[44]	Moderate: differences in weight	Serious, unknown how offered	Low	Low	Low: no missing data	Low	Low	n/a
Autin, 2015[39]	Serious: not discussed	Serious, unknown how offered	Low	Low	No information	Low	Moderate	n/a

Balachandran, 2017[23]	Moderate: sig differences in gender, BMI, comorbidities, previous abdominal surgeries and diagnosis	Serious: unknown who was offered robotic vs lap	Low	Low	Low: excluded missing data	Low	Low	n/a
Buzad, 2013[33]	Moderate: sig differences in gender	Serious for SILC: don't know how they retrospectively chose cases Low for SSRC: consecutive cases in that time frame	Low	Low	Low: no missing data	Low	Low	
Calatayud, 2012[116]	Low: similar groups	Serious: unknown who was offered robotic vs lap	Low	Low	No information	Low	Low	n/a
Chung, 2015[24]	Moderate: sig differences in age, BMI, elective nature, ASA classification, hypertension	Moderate: unknown whether it was consecutive or all cases, unclear how offered	Low	Low	Low: excluded missing data	Low	Low	n/a
Eid, 2020[21]	Serious: acuity of surgeries significantly diff between groups	Serious: unknown how offered	Low	Low	Low (short follow-up)	Low	Low	n/a
Farnsworth, 2018[46]	Moderate: significant differences in primary diagnoses	Serious: prospectively collected ACS registry but don't know	Low	Low	No information	Low	Low	n/a

		how people were offered						
Farukhi, 2017[52]	Serious: not discussed	Serious: unknown how offered	Low	Low	No information	Low	Low	n/a
Gonzalez, 2013[34]	Moderate: sig differences in age and ASA score	Moderate: ALL robotic cases compared to first, consecutive 166 lap cases, but don't know how offered	Low	Low	Low: account for missing data	Low	Low	n/a
Gustafson, 2016[36]	Moderate: BMI and prior abd surgeries significantly diff	Moderate: consecutive cases but don't know how offered	Low	Low	Low: no missing data	Moderate: pt reported outcomes	Low	n/a
Hagen, 2017[25]	Low: patients matched by characteristic	Moderate: don't know how offered but matched	Low	Low	Low: no missing data	Low	Low	n/a
Hagen, 2017[30]	Low: case-matched analysis	Moderate, unknown how offered	Low	Low	No information	Low	Low	n/a
Hawasli, 2016[55]	Moderate: age didn't differ but didn't discuss other sources of bias	Moderate: all cases in time period but didn't discuss how offered	Low	Low	No information	Low	Low	n/a
Higgins, 2017[61]	Serious: don't discuss	Serious: unknown who was offered robotic vs lap	Low	Low	No information	Low	Low	n/a

Jang, 2019[40]	Serious: gender, age, BMI and ASA score differences	Serious, unknown how offered	Low	Low	No information	Moderate: unknown who measured pain scale	Low	n/a
Kaminski, 2014[58]	Moderate: shown but not analyzed differences in age, gender, race. Unsure of significant differences	Serious: unknown who was offered robotic vs lap	Low	Low	Low: excluded missing for outcomes of interest	Low	Low	n/a
Kane, 2020[57]	Low, propensity-matched	Serious: unknown how offered	Low	Low	No information	Low	Low	n/a
Khorgami, 2019[49]	Moderate: no differences, but lumped all surgeries together, no sub-analysis of just cholecystectomy	Serious: unknown who was offered robotic vs lap	Low	Low	No information	Low	Low	n/a
Lee, 2017[26]	Moderate	Moderate: unknown who was offered robotic vs lap	Low	Low	Low	Moderate: patient-reported questionnaire	Low	n/a
Lee, 2018[41]	Moderate: BMI, sex and indication differences	Serious: consecutively performed but unknown how offered	Low	Low	No information	Low	Low	n/a
Lee, 2019[27]	Moderate: differences in age, ASA status, preop and pathologic diagnosis	Moderate: patient decided robot vs lap	Low	Low	No information	Low	Low	n/a

Lescouflair, 2014[42]	Low: matched pts	Serious: consecutively performed but unknown how offered	Low	Low	No information	Moderate: pain measurements	Low	n/a
Li, 2017[28]	Low: similar groups	Serious: unknown who was offered robotic vs lap	Low	Low	No information	Low	Low	n/a
Main, 2017[18]	Moderate: propensity matched analysis, but differences in indication	Serious: unknown who was offered robotic vs lap	Low	Low	No information	Low	Low	n/a
Mitko, 2016[20]	Moderate: indication different	Serious: reviewed all performed but unknown how offered	Low	Low	No information	Low	Low	n/a
Moore, 2016[43]	Moderate: age different	Serious: consecutively performed but unknown how offered	Low	Low	No information	Low	Low	n/a
Pokala, 2019[56]	Serious: groups sig diff in age and race	Serious: unknown how offered (database)	Low	Low	Low (short follow-up)	Low	Low	n/a
Rosemurgy, 2015[50]	Serious: don't discuss	Serious: unknown who was offered robotic vs lap	Low	Low	No information	Low	Low	Didn't report surgical indication/ diagnosis
Ross, 2014[53]	Serious: no discussion	Serious: unknown how offered	Low	Low	No information	Low	Low	n/a

Spinoglio, 2012[37]	Low, similar groups	Low, consecutive cases that matched inclusion criteria matched to 25 consecutive lap cases	Low	Low	Low: no missing data	Low	Low	n/a
Strosberg, 2017[51]	Moderate: differences in BMI, comorbidities and indication	Serious, unknown how offered	Low	Low	Low: no missing data	Low	Low	n/a
Strosberg, 2017[51]	Serious: BMI, comorbidities, indication different	Serious: unknown how offered	Low	Low	No information	Low	Low	n/a
Su, 2017[38]	Low: similar groups	Serious, unknown how offered	Low	Low	Low: no missing data	Moderate: unknown who measured pain scale	Low	n/a
Teoh, 2017[31]	Moderate: similar groups but not addressed what was measured	Serious: unknown how offered	Low	Low	No information	Moderate: unknown who measured pain scale	Low	n/a
Wren, 2011[29]	Low: average age and BMI not significantly different	Moderate: robot offered to all who met inclusion/exclusion criteria and compared to previous sequential lap cases	Low	Low	Low: no missing data	Moderate: pain measurement	Moderate: excluded 1 patient who had conversion	n/a

INGUINAL HERNIA REPAIR

Author, year	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 the reported result	Other source of bias
Abdelmoaty, 2018[75]	Serious: no baseline characteristics reported	Low: database	Low	Low	Low	Low	Low	1 author is a surgical proctor for Intuitive
AlMarqoozi, 2019[71]	Low: similar baseline characteristics and laterality except for age; non-propensity matched	Low: database	Low	Low	Serious: Low 1-yr f/u (6-9%)	Low: complications Moderate: QOL	Low	2 authors (including senior author) receive grants from Intuitive
Bittner, 2018[12]	Moderate: cohorts differed by age, type of job, history of IHR, and use of preop pain meds; BMI not reported but propensity matched	Serious: random consumer sample with, only includes those with survey completion	Serious: recall bias due to study design	Low	Serious: low survey response rate (6%)	Serious: narcotic use, RTW, pain	Low	Study funded by Intuitive; 2 authors (including senior author) employed by Intuitive; 1 author receives consulting fees from Intuitive
Charles, 2018[68]	Moderate: similar baseline characteristics except ASA; non-propensity matched	Low: database	Low	Low	Low	Low: complications, OR times	Low	1 author with grant and travel expenses for educational course from Intuitive
Gamagami, 2018[69]	Low: similar baseline characteristics; propensity matched	Low: consecutive series	Low	Low	Low	Low: complications Moderate: pain not well-defined	Low	Study sponsored by Intuitive; statistical analysis performed by Intuitive; all authors received research grants from Intuitive; 4 authors received

Author, year	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 the reported result	Other source of bias
								consulting and education fees from Intuitive
Holcomb, 2019[84]	Serious: most demographic data not displayed; non-propensity matched	Low: database	Low	Low	Low	Low: complications	Low	
Huerta, 2019[70]	Serious: differs in laterality and hernia complexity; non-propensity matched	Moderate: patients chosen by surgeon expertise	Low	Low	Low	Low: inguinodynia, complications	Low	
Janjua, 2020[77]	Low: differences in age, gender, comorbidities, and laterality; propensity matched	Low: database	Low	Low	Low	Low: LOS	Low	
Kakaishvili, 2018[72]	Serious: baseline characteristics not specified, laterality differs; non-propensity matched	Serious: not specified if consecutive series	Low	Low	Low	Low: OR times, complications Moderate: pain	Low	
Khoraki, 2019[78]	Low: similar baseline characteristics; non-propensity matched	Low	Low	Low	Low	Low: complications	Low	
Knott, 2017[80]	Serious: not propensity matched, adjusted for patient	Low: database	Low	Low	Moderate: unknown follow-up	Low	Low	

Author, year	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 the reported result	Other source of bias
	characteristics but not displayed							
Kolachalam, 2017[66]	Low: similar characteristics, propensity matched	Low: consecutive series for robotic group Moderate: open group patients prior to study initiation	Low	Low	Low	Low	Low	Study sponsored by Intuitive; statistical analysis performed by Intuitive biostatistician; all authors received research grants from Intuitive; 4 authors received consulting and education fees from Intuitive
Kosturakis, 2018[67]	Serious: baseline characteristics differ in hernia laterality and ASA; non-propensity matched	Low: consecutive series	Low	Low	Moderate: unknown follow-up	Low	Low	
Kudsi, 2017[74]	Serious: similar baseline characteristics and laterality except gender and ASA; non-propensity matched	Low: consecutive series	Low	Low	Moderate: missing some data in robot group at f/u	Low: complications, inguinodynia	Low	1st author is consultant for Intuitive
Lammers, 2019[83]	Serious: similar baseline characteristics but not reported; non-propensity matched	Low: consecutive series	Low	Low	Low	Low: OR times, complications	Moderate: spread not reported	

Author, year	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 the reported result	Other source of bias
Macias, 2017[81]	Serious: baseline characteristics and laterality not reported	Serious: not specified if consecutive series	Low	Low	Moderate: unknown follow-up	Low: OR times, inguinodynia	Moderate: limited perioperative and long-term outcomes reported	
Muysoms, 2018[73]	Moderate: similar patient characteristics except baseline QOL, laterality analyzed in subgroups; non-propensity matched	Low: consecutive series for robot Moderate: lap patients from previously published studies	Low	Low	Low	Low: OR times, complications Moderate: QOL/pain	Low	1st author receives consultant fees from Intuitive
Pokala, 2019[82]	Serious: baseline characteristics not completely reported; robot patients more male; non-propensity matched	Moderate: database, severe severity excluded	Low	Low	Low	Low: complications, pain	Low	
Sheldon, 2019[79]	Moderate: similar baseline characteristics except for laterality, other characteristics not reported; non-propensity matched	Serious: institutional data, not stated if consecutive series; patients with intraoperative conversions of approach excluded	Low	Low	Low	Low: narcotic use	Low	
Switzer, 2019[64]	Serious: similar baseline demographics, baseline QOL scores, laterality, but not explicitly reported; non-	Serious: database; excluded patients without 6-mo EuraHS	Low	Low	Low	Low: complications, readmissions, recurrences Moderate: EuraHS QOL	Moderate: complications not specified	

Author, year	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 the reported result	Other source of bias
	propensity matched							
Waite, 2016[65]	Low: similar baseline characteristics, laterality	Low: consecutive series	Low	Low	Low	Low: OR times Moderate: pain scale	Low	1 author became a consultant for Intuitive following preparation of manuscript
Zayan, 2019[76]	Serious: differ by gender, smoking status, co-morbidities, and laterality; non-propensity matched	Serious: not stated if consecutive series, selected based on availability to complete 1-yr f/u survey	Low	Low	Low	Low: LOS, OR times, complications Moderate: QOL	Moderate: limited reporting of complications	

VENTRAL HERNIA REPAIR

Author, year	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 the reported result	Other source of bias
Altieri, 2018[99]	Moderate: differences in ethnicity, gender, BMI; propensity matched but characteristics not reported	Low: database	Low	Low	Low	Low: complications	Moderate: matched outcomes poorly reported and inconsistent with tables	
Armijo, 2018[104]	Moderate: similar characteristics except gender and co-morbidities; non-propensity matched	Low: database	Low	Low	Low	Low: narcotic use, complications	Low	
Bittner, 2018[86]	Serious: differences in co-morbidities, smoking status,	Low	Low	Low	Low	Low: complications	Moderate: no data on	1st author is consultant for Intuitive

Author, year	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 the reported result	Other source of bias
	gender, hernia size; non-propensity matched						recurrences at 90 days	
Carbonell, 2018[90]	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, 2016[100]	Moderate: similar characteristics except for gender; non-propensity matched	Low	Low	Low	Low	Low: complications, recurrence	Low	
Coakley, 2017[98]	Low: similar baseline characteristics; non-propensity matched	Low: database	Low	Low	Low	Low: complications	Low	
Gonzalez, 2015[95]	Low: similar baseline characteristics; non-propensity matched	Low	Low	Low	Moderate: unknown follow-up	Low: complications, recurrence	Low	
Guzman-Pruneda, 2020[91]	Serious: large difference in gender, smoking status, hernia size; non-propensity matched	Low: database	Low	Low	Low	Low: complications, recurrence Moderate: QOL	Low	Operative techniques (*eg* drain placement) were significantly different between comparison groups
Khorgami, 2018[94]	Serious: unable to assess characteristics, as data was pooled for multiple procedures; non-propensity matched	Low: database	Low	Low	Low	Low: LOS	Serious: no other outcomes besides LOS	

Author, year	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 the reported result	Other source of bias
Lu, 2019[93]	Moderate: similar baseline characteristics except for gender and co-morbidities; non-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, 2018[87]	Low: similar baseline characteristics except ASA; propensity matched for hernia size	Low	Low	Low	Low	Low: complications	Low	2 authors are consultants for Intuitive
Mudyanadzo, 2020	Serious: baseline characteristics not reported; non-propensity matched	Serious: institutional data, not stated if consecutive series	Low	Low	Low	Low: pain, narcotic use	Low	
Nguyen, 2017[88]	Moderate: similar characteristics except hernia size; non-propensity matched	Serious: institutional data, not stated if consecutive series	Low	Low	Low	Low: complications	Low	
Prabhu, 2017[96]	Low: similar baseline characteristics; propensity matched	Low: database	Low	Low	Low	Low: complications	Low	1st and senior authors receive grant money from Intuitive
Roberts, 2019[92]	Serious: significantly different hernia defect size, other baseline characteristics not reported; non-propensity matched	Low: database	Low	Low	Low	Low: pain, complications	Low	
Song, 2017[103]	Moderate: characteristics not	Low: database	Low	Low	Low	Low: complications, narcotic use	Low	

Author, year	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 the reported result	Other source of bias
	explicitly reported; propensity matched							
Switzer, 2017[89]	Moderate: similar age, gender, hernia size, other characteristics not explicitly reported; propensity matched	Low: database	Low	Low	Moderate: unknown follow-up	Low: complications, recurrence Moderate: QOL	Moderate: complications outcomes not defined or reported	
Walker, 2018[97]	Moderate: similar baseline characteristics except gender; propensity matched except for gender, and matched characteristics not reported	Serious: institutional data, not stated if consecutive series	Low	Low	Moderate: unknown follow-up	Low: complications, recurrence	Moderate: matched outcomes only selectively reported	2 authors (including senior author) receive honoraria to proctor for Intuitive
Warren, 2016[101]	Serious: similar characteristics except gender, recurrent hernia, and whether TAR performed concurrently; non-propensity matched	Low: database	Low	Low	Low	Low: narcotic use, complications	Low	1st and senior authors are speakers for Intuitive
Zayan, 2019[76]	Serious: difference in gender, BMI, smoking status, baseline QOL; non-propensity matched	Serious: institutional data, not stated if consecutive series	Low	Low	Moderate: unknown follow-up	Low: recurrence Moderate: QOL	Moderate: no outcomes relating to other complications	

APPENDIX G. EVIDENCE TABLES

CHOLECYSTECTOMY

Demographics and Pre-operative Factors

Author **Year** **Population** **Study Design** **US (y/n)** **VA (y/n)**	**# Institutions/ Surgeons**	**Propensity Matching**	**Patient Characteristics Preop** N Age, mean yr (SD) Race/Ethnicity NH-White, % NH-Black, % NH-Asian, % Hispanic, % Male, % BMI, mean (SD) ASA class, mean (SD) Diabetes, % Indication for surgery Acute Chole, N (%) Symptomatic Cholelithiasis, N (%) (*ie*, biliary colic, sludge, chronic cholecystitis) Other, N (%) (*ie*, cancer, polyps, choledocholithiasis, gallstone pancreatitis, *etc*) Elective operation, %								
			Total	**Single-Port Robot**	**Single-Port Lap**	**Multi-Port Robot**	**Multi-Port Lap**	**Unspecified Robot**	**Unspecified Lap**	**Specified combined single and multi- port Robot**	**Specified combined single and multi-port Lap**
Abel S 2019[32] Retrospective cohort Y N	NR/NR	No	N: 584	N: 296 BMI: 32			N: 288 BMI: 31				
Aggarwal R 2020[22] Retrospective cohort N N	Single institution/ Single surgeon	No	N: 40			N: 20 Age: 45.9 (13) Male: 3 (15%) BMI: 28.5 (4.4) ASA 1: 9 (45%) ASA 2: 10 (50%) ASA 3: 1 (5%) Cholecyst: 3 (15%) Biliary colic: 16 (80%) GB polyp: 1 (5.0%) Previous abdominal	N: 20 Age: 48.4 (12.2) Male: 3 (15%) BMI: 31.3 (6.2) ASA 1: 8 (40%) ASA 2: 12 (60%) ASA 3: 0 (0%) Cholecyst: 7 (35%) Biliary colic: 13 (65%) GB polyp: 0 (0%) Previous abdominal surgery: 3 (15%)				

						surgery: 7 (35%)					
Albrecht R 2017[17] Retrospective (matched-pair analysis) N N	Multi- institutional		N: 70			N: 35 Age: 55.5 (17.3) Men: 13 (37.1%) BMI: 28.3 (5.7) ASA I: 10 (28.6%) ASA II: 22 (62.9%) ASA III: 3 (8.6%) Elective: 32 (91.4%)	N: 35 56.9 (16.7) Men: 13 (37.1%) 30.0 (5.2) BMI >30: 14 ASA I: 12 (34.3%) ASAII: 19 (54.3%) ASA III: 4 Elective: 30 (85.7%)				
Altieri MS 2016[45] SPARCS database Prospective cohort Y N	Not reported	Yes	N: 110052					N: 186 NH-W: 69.35% NH-Black: 6.99% NH-Asian: 2.69% Hispanic: 12.37% Male: 34.41% Diabetes: 17.74%	N: 109,866 NH-W: 58.54% NH- Black: 10.95% NH-Asian: 2.89% Hispanic: 18.64% Male: 35.42% Diabetes: 16.48%		
Aragon RJ 2014[44] Prospective observational study Y N	1 institution	No	N: 330 Age: 45 (14) Male: 27% Weight: 88.3 (24.1) Sympt cholelithiasis: 79.1% Acute cholecyst: 13.64% Other: 7.3%	N: 132 Weight: 86.2 (23.6)	N: 36 Weight: 74.4 (15.8)	N; 162 Weight: 93.1 (24.7)					
Autin RL 2015[39] Retrospective analysis Y N	1 institution	No	N: 54	N: 27	N: 27						
Balachandran B 2017[23] Retrospective cohort	1 Surgeon, 1 Institution	No	N: 678 Age: 54.8 (18.6) Male: 209 (30.8%) BMI: 29.6 (6.9) ASA I: 21%	N: 415 Age: 54.1 (18.7) Male: 111 (26.7%) BMI: 29 (6.1) ASA I: 21.5% ASA II: 54.8%			N: 263 Age: 55.8 (18.4) Male: 98 (37.3%) BMI: 30.5 (7.8) ASA I: 20.4% ASA II: 47.8%				

Y N			ASA II: 51.9% ASA III: 25.1% ASA IV: 0% ASA V: 2.0% Diabetes: 112 (16.5%) Acute cholecyst: 173 (25.5%) Chronic cholecyst: 505 (74.5%)	ASA III: 21.8% ASA IV: 0% ASA V: 1.9% Diabetes: 61 (14.9%) Acute cholecyst: 76 (18.3%) Chronic cholecyst: 339 (81.7%)			ASA III: 29.6% ASA IV: 0% ASA V: 2.2% Diabetes: 51 (19.4%) Acute cholecyst: 97 (36.9%) Chronic cholecyst: 166 (63.1%)				
Buzad FA 2013[33] Prospective cohort with historically (retrospective) matched pairs Y N	1 institution/ 1 surgeon	No	N: 30	N: 20 Age: 47.8 (14.9) NH White: 70% (14) Hispanic: 25% (5) Other: 5% (1) Male: 35% (7) BMI: 27.1 (4.7) ASA I: 20% (4) ASA II: 80% (16) Acute cholecyst: 10% (2) Other: 18 (90%)	N: 10 Age: 43.3 (13.7) NH White: 80% (8) Hispanic: 20% (2) Other: 0 Males: 0% (0) BMI: 28.4 (6.2) ASA I: 50% (5) ASA II: 50% (5) Acute cholecyst: 0 Other: 10 (100%)						
Calatayud D 2012 [116] Retrospective analysis Y N	1 Institution	No	N: 187			N: 119 Age: 43.67 Male: 22% BMI: 32.8	N: 68 Age: 44.6 Male: 23.5% BMI: 32.8				
Chung PJ 2015[24] Retrospective cohort Y N	1 Institution/ N/R	No	N: 140	N: 70 Age: 40.3 (15.2) White: 15% Black: 53% Asian-Pacific: 2.0% Male: 14.3% (10) BMI: 29.5 (6.2) ASA I: 11.4% (8) ASA II: 65.7% (46) ASA III: 20% (14) ASA IV: 0 Diabetes: 10% Elective: 46%			N: 70 Age: 47.6 (17.2) White: 59% Black: 9% Asian-Pacific: 1% Male: 18.6% (13) BMI: 32.4 (7.4) ASA I: 4.3% (3) ASA II: 52.9% (37) ASA III: 41.4% (29) ASA IV: 1.4% (1) Diabetes: 19% Elective: 20%				
Eid JJ 2020[21] Retrospective cohort	Single institution/ Multiple surgeons	No	N: 90			N: 20 Age: 44.1 (15.4) Caucasian: 5	N: 70 Age: 42.3 (17) Caucasian: 10 (14.3%)				

Y N						(25%) African-American: 14 (70%) Other/ Decline: 1 (5%) Male: 2 (10%) BMI: 35.7 (9.4) ASA I: 2 (10%) ASA II: 10 (50%) ASA III: 8 (40%) ASA IV: 0 (0%) Diabetes: 2 (10%) Acute cholecyst: 5 (25%) Biliary colic: 12 (60%) Choledocholithiasis: 3 (15%) Biliary dyskinesia: 0 (0%) Outpatient: 19 (95%) ER admission: 1 (5%)	African-American: 58 (82.9%) Other/ Decline: 2 (2.9%) Male: 10 (14.3%) BMI: 34.3 (8.2) ASA I: 6 (8.6%) ASA II: 44 (62.9%) ASA III: 20 (28.6%) ASA IV: 0 (0%) Diabetes: 7 (10%) Acute cholecyst: 26 (37.1%) Biliary colic: 30 (42.9%) Choledocholithiasis: 13 (18.6%) Biliary dyskinesia: 1 (1.4%) Outpatient: 12 (17.1%) ER admission: 58 (82.9%)				
Farnsworth J 2018[46] Observational (prospectively collected registry) Y N	1 institution/ 2 surgeons	No	N: 51					N: 14	N: 37		
Farukhi MA 2017[52] Case control retrospective analysis Y N	1 institution	No	N: 139					N: 69 Morbidly obese: 42	N: 70 Morbidly obese: 19		
Gonzalez AM 2013[34] Retrospective cohort Y N	1 institution (3 hospitals)/ 3 surgeons	No	N: 498	N: 166 Age: 51.6 (15.9) Male: 21.1% (35) BMI: 29.4 (6.2) Mean ASA: 1.84 (0.73) Acute cholecyst: 12% (20)	N: 169 Age: 44.5 (14.3) Male: 23.7% (40) BMI: 29.1 (5.6) Mean ASA: 1.72						

				Sympt cholelithiasis: 76.5% (127) Other: 19 (11.4%)	(0.64)Acute cholecyst: 6.5% (11) Sympt cholelithiasis: 78.7% (133) Other: 11 (6.5%)						
Grochola LF 2019[13] RCT No (Switzerland) No	1 institution/ 3 surgeons	No	N: 60	N: 30 Age: 52.4 (26-82) Race/ethnicity: N/R Male: 10 (33.3%) BMI: 27.3 (3.9) ASA class: N/R Diabetes: n/R Sympt Cholelithiasis: 96.7% (29) Other: 3.3% (1) Elective: 100%	N: 30 Age: 51.5 (30-78) Race/ ethnicity: N/R Male: 14 (46.7%) BMI: 27.3 (4.2) ASA class: N/R Diabetes: N/R Sympt cholelithiasis: 96.7% (29) Other 3.3% (1) Elective: 100%						
Gustafon M 2016[36] Observational (retrospective analysis of prospective database) Y N	1 institution/ 1 surgeon	No	N: 82	N: 38 Age: 48 (14) Race: N/R Male: 21% BMI: 30 (5) ASA mean: 1.5 (1-3) Diabetes: N/R Indication: N/R Elective: N/R	N: 44 Age: 45 (15) Race: n/r Male: 23% BMI: 26 (4) ASA mean: 1.6 (1-3) Diabetes: n/r Indication: n/r Elective: n/r						
Hagen ME 2018[25] Retrospective cohort, matched pair N N	1 Institution	Yes	N: 198	N: 99 Age: 47.4 (12.6) Race: N/R Male: 27.3% (27) BMI: 26.2 (4.2) ASA I and II: 96% (95) III and IV: 4% (4) Diabetes: N/R Sympt cholelithiasis: 100% Elective: N/R			N: 99 Age: 47 (14) Race: N/R Male: 27.3% (27) BMI: 26.3 (4.9) ASA I and II: 96% (95) ASA III and IV: 4% (4) Diabetes: N/R Sympt cholelithiasis: 100% Elective: N/R				
Hagen ME 2018 [30] Retrospective, case-matched analysis	Not reported	No	N: 156	N: 78			N: 78				

Y N											
Hawasli A 2016[55] Observational (retrospective) Y N	1 institution/ 14 surgeons	No	N: 246 Age: 45.4 (17.1) Male: 15.9% (39)							N: 26 (14 single port robot - 53.8%)) Age: 46.2 (11.2)	N: 220 (8 single port lap - 3.6%) Age: 45.3 (17.6)
Heemskerk J 2014[14] Prospective Randomized Trial N N	1 Institution/ 2 surgeons	No	N: 22			N: 11	N: 11				
Higgins RM 2017[61] Surgical Profitability Compass Procedure Cost Manager System Database Retrospective analysis Y N	Not reported	No	N: 381					N: 38	N: 343		
Jang EJ 2019[40] Retrospective analysis N N	2 institutions/ 2 surgeons (1 for SILC and 1 for RSSC)	No	N: 117 Males: 58 (49.6%) ASA 1: 36 (30.8%) ASA 2: 63 (53.8%) ASA 3: 18 (15.4%) Acute cholecyst: 4 (3.4%) Sympt cholelithiasis: 86 (73.5%) Other: 27 (23.1%)	N: 39 Age: 42.03 (10.72) Male: 14 (35.9%) BMI: 28.17 (2.972) ASA 1: 20 (51.3%) ASA 2: 15 (38.5%) ASA 3: 4 (10.3%) Acute cholecyst: 0 Sympt cholelithiasis: 32 (82.1%) Other: 7 (17.9%)	N: 78 Age: 49.76 (12.949) Male: 44 (56.4%) BMI: 27.17 (2.278) ASA 1: 16 (20.5%) ASA 2: 48 (615%) ASA 3: 14 (17.9%) Acute cholecyst: 4 (5.1%) Sympt cholelithiasis: 54 (69.2%) Other: 20 (25.6%)						
Kaminski JP 2014[58] NIS dataset	Not reported	No	N: 735,537					2010 N: 524 Available	2010 N: 362,971 Available		

Retrospective analysis Y N								observations: 451 Age: 53.3 Male: 26.4% (119) Caucasian: 79.6% (359) African American: 10% (45) Hispanic: 7% (31) Asian: 1.1% (5) Native American: 0% (0) Others: 2.3% (10) DM (with and w/o complication): 13.4% Acute cholecyst: 7.1% 2011 N: 1084 Available observations: 991 Age: 55.8 Male: 35.3% (350) Caucasian: 68.2% (676) African American: 11.9% (118) Hispanic: 14.3% (141) Asian: 1.9% (19) Native American: 0.5% (5) Others: 1.8% (18) DM (w/ or w/o complication): 21.5% Acute	observations: 327,803 Age: 49.3 Male: 32.9% (107,941) Caucasian: 65.3% (214,074) African American: 10.3% (33,656) Hispanic: 18.6% (60,848) Asian: 2.2% (7,366) Native American: 0.8% (2,501) Others: 2.9% (9,358) DM (w/ or w/o complication): 16.8% Acute cholecyst: 39.2% 2011 N: 370,958 Available observations: 338,702 Age: 51.1 Male: 34.1% (115,406) Caucasian: 63.7% (215,916) African American: 10.1% (34,072) Hispanic: 20.2% (68,541) Asian: 2.0% (6,685) Native American: 0.7% (2,254) Others: 3.3% (11,234)		

								cholecyst: 10.8%	DM (w/ or w/o complication): 17.6% Acute cholecyst: 41.7%		
Kane WJ 2020[57] Retrospective Cohort Y N	Single institution/ Multiple surgeons	Yes	N: 1066					N: 106 Age: 41.5 (30-56)* White: 80 (75.5%) Male: 30 (28.3%) BMI: 30.1 (26.5-36.4)* Diabetes: 7 (6.6%)	N: 1060 Age: 43 (30-58)* White: 806 (76%) Male: 313 (29.5%) BMI: 30.2 (26.5-35.2)* Diabetes: 79 (7.5%)		
Khorgami Z 2019[49] NIS Retrospective analysis Y N	Not reported	No	N: 70,673					N: 1,271	N: 69,402		
Kudsi OY 2017[15] Randomized controlled trial Mixed (7 institutions in US, 1 in Greece) N	8 institutions/ 10 surgeons		N: 136	N: 83 Age: 46.8 (15.5) Caucasian: 46 (55%) African-American: 9 (11%) Asian: 3 (4%) Hispanic: 25 (30%) Male: 18 (21%) BMI: 30.4 (6.5) ASA I: 17 (20%) ASA II: 52 (63%) ASA III: 13 (16%) ASA IV: 1 (1%) DM: 5 (6%) Acute cholecyst: 0 Sympt cholelithiasis: 69 (83.1%) Other: 14 (16.8%) Elective: 100%			N: 53 46.5 (17.3) Caucasian: 29 (55%) African-American: 7 (13%) Asian: 0 (0%) Hispanic: 17 (32%) Male: 4 (7%) BMI: 31.7 (6.7) ASA I: 11 (21%) ASA II: 34 (64%) ASA III: 8 (15%) ASA IV: 0 (0%) DM: 4 (8%) Acute cholecyst: 0 Sympt cholelithiasis: 47 (86.7%) Other: 7 (13.2%) Elective: 100%				
Lee EK 2017[26] Retrospective analysis		No	N: 120 Male: 42.5%	N: 60 Age: 42.53 (9.92) Male: 28 (46.7%) BMI: 24.45 (3.63) ASA I: 37 (61.7%)			N: 60 Age: 46.58 (12.44) Male: 23 (38.3%) BMI: 24.67				

N N				ASA II: 23 (38.3%) Acute cholecyst: 0 (0%) Sympt cholelithiasis: 13 (15.1%) Other: 73 (84.9%)			(4.01) ASA I: 74 (61.7%) ASA II: 46 (38.3%) Acute cholecyst: 7 (4%) Sympt cholelithiasis: 48 (27.1%) Other: 122 (68.9%)				
Lee JH 2018[41] Retrospective analysis Y N	1 institution/ 2 surgeons	No	N: 630	N: 520 Age: 48 (10.1) Male: 135 (25.9%) BMI: 23.9 (3.6) Sympt cholelithiasis: 72.2%	N: 110 Age: 36.4 (9.6) Male: 8 (7.3%) BMI: 21.8 (2.4) Sympt cholelithiasis: 67.4%						
Lee SR 2019[27] Retrospective analysis N N	1 institution/ 1 surgeon	No	N: 121 Age: 46.8 (11.64) Male: 52 (51.2%) BMI: 25 (3.59) ASA 1: 85 (70.2%) ASA 2: 36 (29.8%) Acute cholecyst: 0 (0%) Sympt cholelithiasis: 69 (57.0%) Other: 38 (43.0%)	N: 61 Age: 42.69 (8.95) Male: 34 (55.7%) BMI: 24.78 (3.62) ASA 1: 38 (62.3%) ASA 2: 23 (37.7%) Acute cholecyst: 0 (0%) Sympt cholelithiasis: 23 (37.7%) Other: 38 (62.3%)			N: 60 Age: 50.33 (12.82) Male: 28 (46.7%) BMI: 25.23 (3.57) ASA 1: 47 (78.3%) ASA 2: 13 (21.7%) Acute cholecyst: 0 (0%) Sympt cholelithiasis: 46 (76.7%) Other: 14 (23.4%)				
Lescouflair T 2014[42] Retrospective review of prospectively maintained database Y N	1 institution/ 1 surgeons		N: 82	N: 41	N; 41						
Li YP 2017[28] Retrospective analysis N N	1 institution/ 2 surgeons	No	N: 445	N: 78 Age: 56.69 (13.35) Male: 37 (48.3%) BMI: 24.17 (3.01) Sympt cholelithiasis: 53 (68%)			N: 367 Age: 51.44 (14.11) Male: 161 (43.9%) BMI: 25.63 (4.13) Sympt				

				Acute cholecyst: 17 (21.8%) Other: 8 (10.3%)			cholelithiasis: 235 (64%) Acute cholecyst: 91 (24.8%) Other: 41 (11.2%)				
Main WPL 2017[18] Retrospective analysis Y N	1 institution	Yes	N: 1133			N: 179 Age: 47.19 (14.92) BMI: 38.85 (7.29) ASA I: 10 ASA II: 107 ASA III: 58 ASA IV: 4	Before propensity score matching N: 1133 Age: 46.38 (16.41) BMI: 36.89 (5.95) ASA I: 46 ASA II: 520 ASA III: 373 ASA IV: 15 After Propensity Score Matching N: 358 Age: 45.91 (15.12) BMI: 38.75 (6.72) ASA I: 25 ASA II: 216 ASA III: 112 ASA IV: 5				
Mitko J 2016[20] Retrospective analysis Y N	1 institution	No	N: 1133			N: 179 BMI: 38.8 Acute cholecyst: 6% Chronic cholecyst: 93%	N: 954 BMI: 36.8 Acute cholecyst: 11.7% Chronic cholecyst: 87%				
Moore MD 2016[43] Retrospective analysis Y N	1 institution/ 2 surgeons	No	N: 50	N: 21 Age: 47 (15) Male: 5 (24%) BMI: 26 (3) ASA 1 : 2 (9.5%) ASA 2: 14 (66.7%) ASA 3 or higher: 5 (23.8%) Acute cholecyst: 2 (9.5%) Sympt cholelithiasis: 17 (80.9%) Other: 2 (9.5%)	N: 29 Age: 37 (15) Male: 3 (10%) BMI: 28 (6) ASA 1: 4 (13.8%) ASA 2: 22 (75.9%) ASA 3 or higher: 3 (10.3%) Acute cholecyst: 5 (17.2%) Sympt cholelithiasis: 21 (72.4%)						

					Other: 3 (2.77%)						
Pietrabissa A 2016[16] Prospective, randomized, double-blind trial N N	1 institution/ 4 surgeons	No	N: 60	N: 30			N: 30				
Pokala B 2019[56] Retrospective analysis of Vizient database Y N	Multi- institution/ multi- surgeons	No	N: 91849					N: 1971 Age 18-30yrs: 215 (10.9%) Age 31-50yrs: 699 (35.5%) Age: 51-64yrs: 531 (26.9%) Age ≧ 65: 526 (26.7%) White: 1317 (67.9%) Black: 334 (17.2%) Other: 288 (14.9%) Male: 660 (33.5%)	N: 89878 Age 18-30yrs: 16144 (17.9%) Age 31-50yrs: 31553 (35.1%) Age: 51-64yrs: 21084 (23.4%) Age ≧ 65: 21197 (23.6%) White: 56553 (65.2%) Black: 10906 (12.6%) Other: 19306 (22.3%) Male: 30194 (33.6%)		
Rosemurgy A 2015[50] Retrospective analysis Y N	1 institution	No	N: 232					N: 31 Elective: 100%	N: 201		
Ross S 2014[53] Retrospective analysis Y N	1 institution	No	N: 232					N: 31	N: 201		
Spinoglio G 2012[37] Retrospective analysis N Y	1 institution/ 1 surgeon	No	N: 50	N: 25 Age: 54.2 (17.1) Male: 5 (20%) BMI: 23.7 (3.9) Sympt cholelithiasis: 23 (92%) Acute cholecyst: 0 Other: 2 (8%) Elective: 100%	N: 25 Age: 52.5 (17.9) Male: 3 BMI: 24.5 (4.7) Acute cholecyst: 0 Elective: 100%						

Strosberg DS 2016[54] Retrospective analysis Y N	1 institution	No	N: 156					N: 142 Sympt cholelithiasis: 92 (64.79%) Acute cholecyst: 1 (0.7%) Other: 27 (19.01%)	N: 114 Sympt cholelithiasis: 54 (47.3%) Acute cholecyst: 14 (12.28%) Other: 9 (7.89%)		
Strosberg DS 2017[51] Retrospective analysis Y N	1 institution/ 1 surgeon	No	N: 237					N: 140 Age 47 (17- 94) Male: 44 (32.4%) White: 120 (85.7%) BMI: 30.3 (17.1-68.8) Diabetes: 20 (14.3%) Sympt cholelithiasis: 83 (59.3%)	N: 97 Age: 47 (17- 82) Male: 31 (32%) Whit: 82 (84.5%) BMI: 28.8 (18.9-46.4) Diabetes: 16 (16.5%) Sympt cholelithiasis: 52 (53.6%)		
Su WL 2016[38] Retrospective analysis N Y	1 institution	No	N: 114	N: 51 Age: 53.64 (15.54) Male: 18 (35.29%) BMI: 23.6 (3.8) Sympt cholelithiasis: 33 (64.7%) Acute cholecyst: 10 (19.61%) Other: 8 (15.69)	N: 63 Age: 50.94 (13.79) Male: 23 (36.51%) BMI: 246 (3.11) Sympt cholelithiasis: 37 (58.73%) Acute cholecyst: 15 (23.81%) Other: 15 (23.81%)						
Teoh AY 2017[31] Prospective comparative study Not reported N	2 hospitals	No	N: 24	N: 14			N: 10				
Wren SM 2011[29] Prospective analysis of SSRC with retrospective comparison to lap chole	1 institution	No	N: 20	N: 10 Age: 58.1 (15.9) BMI: 27.7 (3.3) Male: 7 (70%) Sympt cholelithiasis: 100%			N: 10 Male: 7 (70%) Age: 61.8 (15.6) BMI: 28.4 (6.2)				

Y Y											

cholecyc = cholecystitis; cholelith = cholelithiasis; sympt = symptomatic

Intra-operative Outcomes

Author **Year** **Population** **Study Design** **US (y/n)** **VA (y/n)**	**Intraoperative Outcomes (<30d)** OR, time, min (SD) EBL, mL (SD) Transfusions, % Conversion To Open, % To Lap, % Major Complications, N (%)							
	Single-Port Robot	**Single-Port Lap**	**Multi-Port Robot**	**Multi-Port Lap**	**Unspecified Robot**	**Unspecified Lap**	**Specified combined single and multi-port Robot**	**Specified combined single and multi-port Lap**
Abel S 2019[32] Retrospective cohort Y N								
Aggarwal R 2020[22] Retrospective cohort N N			OR time: 86.5 (60.5-106.5)* Docking time: 11.5 (9-13)* Console time: 30.8 (23.5-35)* Intraoperative event (bleeding): 1 (5.0%) Conversion to lap: 2 (10%)	OR time: 31.5 (26-41)* Intraoperative event: 0 (0%)				
Albrecht R 2017[17] Retrospective (matched-pair analysis) N N			OR time: 104.2 (44.8) Conversion: 2 Complications: 8 (bleeding: 2, gallbladder opening: 4, other: 2)	OR time: 91.9 (38.5) Conversion: 1 Complications: 3 (bleeding: 1, gallbladder opening: 2)				
Altieri MS 2016[45] SPARCS database Prospective cohort Y N								
Aragon RJ 2016[45] Prospective	OR time: 81.3 (23.3)	OR time: 62.3 (21.6)	OR time: 80.9 (24.8)					

observational study Y N	Case start time: 10.1 (8.7) Setup time: 4.4 (2.7) Robot time: 39.7 (15) Cases "not completed via intended approach": 13 (9.8%) Conversion to lap: 7.6% Conversion to open: 0.7%	Cases "not completed via intended approach": 4 (11.1%) Conversion to lap: 5.6%	Case start time: 17.2 (8.7) Setup time: 6.3 (3.7) Robot time: 38.2 (15.5) Cases "not completed via intended approach": 7 (4.3%) Conversion to lap: 3.7% Conversion to open: 0.6%					
Autin RL 2015[39] Retrospective analysis Y N								
Balachandran B 2017[23] Retrospective cohort Y N	OR time: 89.4 (27.8) Robotic time: 57 (14.7) Docking time: 6.8 (5.2) EBL: Minimal Conversion to Open: 13 (3.2%) Conversion to Lap : 12 (2.9%) Major complications: 0			OR time: 92.6 (31.9) EBL: Minimal Conversion to open: 13 (4.9%) Major complications: 0				
Buzad FA 2013[33] Prospective cohort with historically (retrospective) matched-pairs Y N	Docking time: 6.6 (2.0) Console time: 50.7 (17.9) Incision to close: 84.6 (20.5) EBL 8.4 (7.3) Transfusions: 0 Major complications: 0	Incision to close: 85.5 (11.8) EBL: 12.0 (7.5) Transfusions: 0 Major complications: 0						
Calatayud D 2012[116] Retrospective analysis Y N			OR time: 90.81 Conversion to open: 0	OR time: 89.45 Conversion to open: 2				
Chung PJ 2015[24] Retrospective cohort Y N	Docking time: 11.5 (5.7) Console time : 52.8 (5.7) OR time: 111.5			OR time: 106 (41) Conversion to open: 11 (15.7%)				

	(31.1) EBL: N/R Conversion to open: 1.4% (1)							
Eid JJ 2020[21] Retrospective cohort Y N			OR time: 93.4 (15.4) EBL: 10.8 (9.9) CBD Injury: 0 (0%) Conversion to open: 0 (0%)	OR time: 101.3 (49.1) EBL: 21.7 (32) CBD Injury: 1 (1.4%) Conversion to open: 3 (4.3%)				
Farnsworth J 2018[46] Observational (prospectively collected registry) Y N					OR time: 158 (38) Conversion to open: 0	OR time: 135 (62) Conversion to open: 5 (1.5%)		
Farukhi MA 2017 [52] Case control retrospective analysis Y N								
Gonzalez AM 2013[34] Retrospective cohort Y N	Surgical time (skin to close): 63 (25.2) Conversion to Open: 0% (0)	Surgical time (skin to close): 37.1 (13.3) Conversion to Open: 0% (0)						
Grochola LF 2019[13] RCT No (Switzerland) No	Console time: 35 (21-107) OR time: 85.5 (48-148) EBL: 5.0 (0-150) Conversion to Open: 0 Conversion to 4 port LC: 2 Complications: 40% (12): 8 peritoneal tears + 4 minor bleeding	OR time: 74 (31-135) EBL: 3.5 (0-300) Conversion to Open Conversion to 4 port LC: 3 Complications: 46.7% (14): 11 peritoneal tears + 3 minor bleeding						
Gustafon M 2016[36] Observational (retrospective analysis of prospective database) Y N	OR time: 98 (37) Conversion to multiport or open: 8% Major complications: 0	OR time: 68 (19) Conversion to multiport or open: 11% Major complications: 0						

Hagen ME 2018[25] Retrospective cohort, matched pair N N	OR time: 97 (39) Conversion: 4% (4) Complications: 4% (4) Bleeding: 2% (2) Organ lesion: 2% (2)			OR time: 93.5 (32.5) Conversion: 1% (1) Complications: 0				
Hagen ME 2017 [30] Retrospective, case-matched analysis Y N	OR time: 93.9			OR time: 82.5				
Hawasli A 2016[55] Observational (retrospective) Y N							Case time: 121 (15.4) OR time: 86.6 (14.3)	Case time: 98.4 (27.5) OR time: 63.9 (25.9)
Heemskerk J 2014[14] Prospective Randomized Trial N N			OR (skin to close): 86 Conversions: 0 Major complications: 0	OR (skin to close): 48 Conversions: 0 Major complications: 0				
Higgins RM 2017[61] Surgical Profitability Compass Procedure Cost Manager System Database Retrospective analysis Y N					Mean case duration: 84.3 (25.2)	Mean case duration: 75.5 (30.1)		
Jang EJ 2019[40] Retrospective analysis N N	OR time: 107.92 (24.950) Conversion (to lap or open): 2 (5.1%) Bile spillage during operation: 6 (15.4%) Use of additional robotic arm or port: 0 Complication: 0	OR time: 60.99 (17.810) Conversion (to lap or open): 2 (2.6%) Bile spillage during operation: 9 (11.5%) Use of additional robotic arm or port: 10 (12.8%) Complication: 5 (6.4%)						
Kaminski JP 2014[58] NIS dataset Retrospective analysis Y N					2010 Conversions: 0% Intraoperative complications: 4.5%	2010 Conversions: 0.32% Intraoperative complications: 1.4% 2011		

					2011 Conversions: 1.66% Intraoperative complications: 4.0%	Conversions: 0.29% Intraoperative complications: 1.3%		
Kane WJ 2020[57] Retrospective Cohort Y N					OR time: 185 (175-195)*	OR time: 160 (135-175)*		
Khorgami Z 2019[49] NIS Retrospective analysis Y N								
Kudsi OY 2017[15] Randomized controlled trial Mixed (7 institutions in US, 1 in Greece) N	OR time: 61 (27.5) EBL: 13.06mL Transfusions: 0 (0%) Coversions to open: 0 (0%) Intraoperative complications: 0 (0%)			OR time: 44 (19.9) EBL: 15.83mL Transfusions: 0 (0%) Conversions to open: 0 (0%) Intraoperative complications: 0 (0%)				
Lee JH 2019[27] Retrospective analysis Y N	OR time: 46.9 (12.1) Docking time from incision to completion fo docking procedure: 7.1 (5-20) Console time: 17.8 (5-65) Conversion to open: 0 Conversion to lap (4-port): 3 Intraoperative bile spillage: 5.4%	OR time: 53.4 (16.6) Conversion to open: 0 Conversion to 3-port lap procedure: 3 Addition of 1 additional port: 5 Intraoperative bile spillae: 7.4%						
Lescouflair T 2014[42] Retrospective review of prospectively maintained database Y N	OR time: 96. Conversion rate: 9%	OR ime: 65.2 Conversion rate: 11%						
Lee EK 2017[26] Retrospective analysis N N	OR time (total): 121.6 (22.2) Anesthesia time: 115.7 (22.3) Surgery time: 86.8 (21.7)			OR time (total): 71.9 (10.4) Anesthesia time: 65.9 (10.5) Surgery time: 34 (9.6)				

Lee SR 2018[41] Retrospective analysis N N	Docking time: 10.75 (4.33) Console time: 44.84 (13.83) Total OR time: 95.32 (20.27) Total OR time minus docking time: 82.77 (18.27 EBL: 38.20 (27.05) LOS: 2.26 (0.92) Intraoperative complications: 0 (0%)			Total OR time: 37.67 (19.73) EBL: 34.33 (32.59) LOS: 2.43 (1.73) Intraoperative complications: 0 (0%)				
Li YP 2017[28] Retrospective analysis N N	OR time: 75.7 (31.3) Conversion to open or lap: 0 (0%)			OR time: 64.37 (30.61) Conversion to open: 7 (1.9%)				
Main WPL 2017[18] Retrospective analysis Y N			OR time: 80 (29.12) Conversion to open: 0 (0%)	OR time: 60.22 (29.78) Conversion to open: 0 (0%)				
Mitko J 2016[20] Retrospective analysis Y N			OR time: 80	OR time: 62				
Moore MD 2016[43] Retrospective analysis Y N	OR time (skin to skin): 120 (32) EBL (median): 10 (0-50) Conversion to open: 0 Additionalports: 0 Intraoperative complications: 0	OR time (skin to skin): 79 (35) EBL (median): 10 (5-150) Conversion to open: 0 Additional ports: 3 (10%) Intraoperative complications: 0						
Pietrabissa A 2016[16] Prospective, randomized, double-blind trial N N	OR time (total): 98 (34) Docking time: 23 (7) Dissection time: 56 (26) Closure time: 19 (5) Bile spillage: 2 (6%) Minor bleeding: 3 (10%) Liver damage at GB fossa: 1 (3%) Conversions: 0			OR time (total): 87 (30) Dockingtime: 15 (6) Dissection time: 44 (16) Closure time: 11 (5) Bile spillage: 5 (16%) Minor bleeding: 4 (13%) Liver damage at GB fossa: 3 (10%) Conversions: 0				

Pokala B 2019[56] Retrospective analysis of Vizient database Y N								
Rosemurgy A 2015[50] Retrospective analysis Y N					OR time: 141 (25.38)	OR time: 102 (32.7)		
Ross S 2014[53] Retrospective analysis Y N					OR time: 141 (25.38)	OR time: 102 (32.7)		
Spinoglio G 2012[37] Retrospective analysis N Y	OR time: 62.7 (16.6) Intraoperative complications: 0	OR time: 83.2 (21.1) Intraoperative complications: 0						
Strosberg DS 2016[54] Retrospective analysis Y N					OR time: 80 Conversion to open: 1 (0.7%) EBL: 20.15	OR time: 68 Conversion to open: 7 (6.14%) EBL: 42.01		
Strosberg DS 2017[51] Retrospective analysis Y N					OR time: 74.5 (47-293) EBL: 10 (2-200) Transfusions: 0 (0%) Conversions to open: 1 (0.7%)	OR time: 56 (35-244) EBL: 10 (5-600) Transfusions: 1 (1%) Conversion to open: 7 (7.2%)		
Su WL 2016[38] Retrospective analysis N Y	OR time: 71.30 (48.88) Conversion rate: 0	OR time: 74.70 (30.16) Conversion rate: 2 (3.17%)						
Teoh AY 2017[31] Prospective comparative study Not reported N	OR time: 62.3 (22.6) Conversion: 0			OR time: 72.1 (19.2) Conversion: 0				
Wren SM 2011[29] Prospective analysis of SSRC with retrospective comparison to lap chole Y Y	OR time: 105.3 (82-139) Major complications: 0 Conversion: 1 (1%)			OR time: 106.1 (70-142) Major complications: 1 (10%) Conversion: 0				

Short-term Outcomes

Author **Year** **Population** **Study Design** **US (y/n)** **VA (y/n)**	**Short-Term Outcomes (<30d)** Readmissions, mean (SD) ED visits, mean (SD) LOS, mean days (SD) Mortality, N (%) Complications, N (%) Common Bile Duct Injury, N (%) Bile Leak, N (%) Retained stone, N (%) Reoperation, N (%) Pain Narcotic use Return to work							
	Single-Port Robot	**Single-Port Lap**	**Multi-Port Robot**	**Multi-Port Lap**	**Unspecified Robot**	**Unspecified Lap**	**Specified combined single and multi-port Robot**	**Specified combined single and multi-port Lap**
Abel SA 2019[32] Retrospective cohort Y N	Postoperative complications: 43 (15%)			Postoperative complication: 41 (14%)				
Aggarwal R 2020[22] Retrospective cohort N N			Postoperative events: 5 (25%) Bile Leak: 0 (0%) Wound infection :1 (5%) Bowel obstruction: 1 (5%) Constipation: 1 (5%) Gastroenteritis: 1 (5%) Pain: 1 (5%)	Postoperative events: 5 (25%) Bile Leak: 1 (5%) Wound infection :3 (15%) Bowel obstruction: 0 (0%) Constipation: 0 (0%) Gastroenteritis: 0 (0%) Pain: 1 (5%)				
Albrecht R 2017[17] Retrospective (matched-pair analysis) N N			Postoperative LOS: 3.8 (4.7) Total LOS: 3.9 (4.8) Postoperative pain: 11 (50%) Postoperative pain duration (None= 0, Less than 5d = 1, Less than 1 wk= 2, Between 7-14 days= 3, More than 2 weeks = 4): 1.55 (1.77)	Postoperative LOS: 2.8 (1.3) Total LOS: 3.5 (2.3) Postoperative pain: 8 (34.8%) Postoperative pain duration (None= 0, Less than 5d = 1, Less than 1 wk= 2, Between 7-14 days= 3, More than 2 weeks = 4): 0.74 (1.18) Reoperation: 0				

			Reoperation: 1 (4.5%)					
Altieri MS 2016[45] SPARCS database Prospective cohort Y N					LOS: 4.92 (8.95) Complications: 38 (20.43%)	LOS: 5.7 (8.71) Complications: 22,618 (20.59%)		
Aragon RJ 2014[44] Prospective observational study Y N	Requirement for hospital stay: 8.3% Hospital readmission: 6.8% Reoperation: 1	Requirement for hospital stay: 0% Hospital readmission: 11.1% Reoperation: 1	Requirement for hospital stay: 0.6% Hospital readmission: 0.6%					
Autin RL 2015[39] Retrospective analysis Y N								
Balachandran B 2017[23] Retrospective cohort Y N	Readmission: 13 (3.1%) ED Visits: 38 (9.2%) LOS: 1.9 (3.1) Bile leakage: 1 (0.2%) Wound infection: 16 (3.9%) Abdominal pain: 35 (8.4%)			Readmission: 4 (1.5%) ED visits: 14 (5.3%) LOS: 2.4 (2.3) Bile leakage: 2 (0.8%) Wound infection: 3 (1.1%) Abdominal pain: 11 (4.2%)				
Buzad FA 2013[33] Prospective cohort with historically (retrospective) matched-pairs Y N	Readmission: 1 Pain: 1	Readmission: 0 ED visit: 1 Pain: 1 Wound infection: 1						
Calatayud D 2012[116] Retrospective analysis Y N			LOS: 1.39 CV Grade 1&2: 19.3%	LOS: 1.37 CV Grade 1&2: 17.6% Bile leak: 1				
Chung PJ 2015[24] Retrospective	Readmissions: 2.8% (2) LOS: 1.5 (3.8)	Readmissions: 4.3% (3) LOS: 3.2 (3.6)						

cohort Y N	Mortality: 0 Common Bile Duct: 0 Retained stone: 1	Mortality: 0 Common Bile Duct: 0 Pain: 1 (requiring readmission)							
Eid JJ 2020[21] Retrospective cohort Y N			30d Readmission: 0 (0%) LOS: 0.8 (0.4) Bleeding: 0 (0%) UTI: 1 (5%) SSI: 1 (5%)	30d Readmission: 0 (0%) LOS: 2.7 (2.1) Bleeding: 2 (2.8%) UTI: 0 (0%) SSI: 0 (0%)					
Farnsworth J 2018[46] Observational (prospectively collected registry) Y N					LOS: 1.4 (1.4)	LOS: 2.4 (2.6)			
Farukhi MA 2017[52] Case control retrospective analysis Y N									
Gonzalez AM 2013[34] Retrospective cohort Y N	LOS: 1.2 (2.2)Complication rate: 1.8% (3) Superficial Site infection: 1 Deep surgical site infection: 2	LOS: 1.3 (5.3) Complication rate: 1.8% (3) Retained stone: 1							
Grochola LF 2019[13] RCT No (Switzerland) No	LOS: 1.9 (1-4) Complications: 13.3% (4) Grade I: 6.7% (2) Grade II: 6.7% (2) Grade III: 0 Grade IV: 0 Grade V: 0 Superficial wound infection: 3.3% (2)	LOS: 3.06 (1-26) Complications: 23.3% (7) Grade I: 13.3% (4) Grade II: 3.3% (1) Grade III: 3.3% (1) Grade IV: 3.3% (1) Grade V: 0 Superficial wound infection: 3.3% (1) Retained stone: 3.3% (1)							

Gustafon M 2016[36] Observational (retrospective analysis of prospective database) Y N	Readmissions: 0 LOS (Number of patients staying >24hrs): 1 Complications: 0 Days taking narcotics (mean): 2.3 (1.3) Days until return to normal funtion (mean): 4.0 (2.0)	Readmissions: 0 LOS (Number of patients staying >24hrs): 0 Complications: 0 Days taking narcotics (mean): 1.7 (1.2) Days until return to normal function (mean): 2.3 (1.1)						
Hagen ME 2018[25] Restrospective cohort, matched pair N N	LOS: 1.9 (1.7) Minor complication (Clavien I or II): 2% (2) Major compication (Clavien II or higher): 1% (1)			LO: 1.7 (1.6) Minor complication (Clavien I or II): 2% (2) Major complication (Clavien II or higher): 1% (1)				
Hagen ME 2017[30] Retrospective, case-matched analysis Y N	LOS: 2.4 Reoperation: 0			LOS: 2.3 Reoperation: 0				
Hawasli A 2016[55] Observational (retrospective) Y N							LOS: 1.0 (0)	LOS: 1.02 (0.15)
Heemskerk J 2014[14] Prospective Randomized Trial N N								
Higgins RM 2017[61] Surgical Profitability Compass Procedure Cost Manager System Database Retrospective analysis					Mean LOS: 1.0 (0)	Mean LOS: 1.1 (0.3)		

Y N								
Jang EJ 2019[40] Retrospective analysis N N	LOS: 1.79 (1.031) Pain score after immediate surgery: 4.95 (1.905) Pain score at discharge: 1.92 (0.900)	LOS: 2.38 (1.209) Pain score after immediate surgery: 5.00 (1.405) Pain score at discharge: 2.35 (1.209)						
Kaminski JP 2014[58] NIS dataset Retrospective analysis Y N					2010 LOS: 3.63 2011 LOS: 4.59	2010 LOS: 4.14 2011 LOS: 4.1		
Kane WJ 2020[57] Retrospective Cohort Y N					30d readmission: 0 (0%) LOS: 0.1 (0.7)	30d readmission: 27 (2.6%) LOS: 0.8 (1.9)		
Khorgami Z 2019[49] NIS Retrospective analysis Y N					LOS: 2.9 (2)	LOS: 2.8 (2.1)		
Kudsi OY 2017[15] Randomized controlled trial Mixed (7 institutions in US, 1 in Greece) N	LOS: 16.67 hours Postoperative complications: 4 (5%) Bile leak: 0 (0%) Wound infection: 2 (%) DVT/PE: 1 (1%)			LOS: 13.93 hours Postoperative complications: 2 (4%) Bile leak: 1 (2%) Wound infection: 1 (2%)				
Lee EK 2017[26] Retrospective analysis N N	LOS: 4.3 (0.5) No of analgesics given (preop): 0 (0-0) No of analgesics given during surgery: 1 (0-3) No of analgesics given (recovery room): 0 (0-1) No. of analgesics given (postop): 1 (0-9)			LOS: 4.7 (0.8) No of analgesics given (preop): 0 (0-4) No of analgesics given during surgery: 1 (0-3) No of analgesics given (recovery room): 0 (0-0) No. of analgesics given (postop): 1 (0-6)				

	Pain level (preop): 4 (0-8) 6hrs postop: 2 (0-5) First day postop: 2 (0-4) Second day postop: 0 (0-4) One week postop: 0 (0-2)			Pain level (preop): 0 (0-8) 6hrs postop: 2 (0-5) First day postop: 2 (0-6) Second day postop: 2 (0-5) One week postop: 2 (0-3)				
Lee SR 2019[27] Retrospective analysis N N	Postoperative complications: 0 (0%) Wound infection: 0 Bile leak: 0 Pain rating score (1h): 4.75 (1.24) Pain rating score (6h): 2.54 (0.59) Pain rating score (1d): 2.25 (1.02)			Postoperative complications: 0 (0%) Wound infection: 0 Bile leak: 0 Pain rating score (1h): 4.70 (1.22) Pain rating score (6h): 2.85 (1.24) Pain rating score (1d): 2.55 (1.12)				
Lee JH 2018[41] Retrospective analysis Y N	LOS: 3.3 (1.7) Bile duct injury: 0	LOS: 4.0 (1.8) Bile duct injury: 0						
Lescouflair T 2014[42] Retrospective review of prospectively maintained database Y N	Narcotic use duration: 2.4 Time to independent performance of daily activities: 4	Narcotic use duration: 1.6 Time to independent performance of daily activities: 4						
Li YP 2017[28] Retrospective analysis N N	LOS: 3.73 (1.77) Mortality: 0 (0%) Complications: 3 (3.8%) CG grade I: 2 (2.5%) CV Grade II: 0 (0%) CV Grade III-a: 0 (0%) CV Grade III-b: 1 (1.28%) CV Grade IV: 0 (0%) Residual CBD Stone: 0 (0%) Bile leak: 0 (0%)			LOS: 4.35 (0.75) Mortality: 0 (0%) Complications: 75 (20.4%) CV Grade I: 50 (13.6%) CV Grade II: 14 (3.81%) CV Grade III-a: 9 (2.45%0) CV Grade III-b: 2 (0.55%) CV Grade IV: 0 (0%) Residual CBD Stone: 2 Bile leak: 2 Biliary stricture: 2				

	Biliary stricture: 0 (0%) Subhepatic fluid collection: 0 (0%) Wound infection: 0 (0%) Analgesic requirement (days): 0.64 (2.11)			Subhepatic fluid collection: 3 Analgesic requirement (days): 1.13 (3.30) Wound infection: 10 (2.7%)				
Main WPL 2017[18] Retrospective analysis Y N			ED visits: 13 (7.2%) Bile lek: 2 (1.1%) Retained CBD Stone: 3 (1.67%) Mortality: 0 (0%) SSI: 2 (1.1%) Present to ER w/ abd pain: 1 (0.55%)	ED visits: 69 (7.2%) Bile leak: 8 (0.83%) Retained CBD Stone: 2 (0.2%) Mortality: 3 (0.3%) SSI: 4 (0.41%) Present to ER w/ abd pain: 31 (3.2%)				
Mitko J 2016[20] Retrospective analysis Y N			LOS: 0.23 Readmission (for abdominal pain): 0.55% Retained stone: 1.7%	LOS: 0.58 Readmission (for abdominal pain): 3.2% Retained stones: 0.21%				
Moore MD 2016[43] Retrospective analysis Y N	LOS (hours): 9.9 (6.7) Postoperative complications: 1 (4.8%) Choledocholithiasis: 1	LOS (hours): 13.1 (13.9) Postoperative complications: 2 (6.9%) Choledocholithiasis: 1 Wound infection: 1						
Pietrabissa A 2016[16] Prospective, randomized, double-blind trial N N	LOS: 1.2 (1-3) Wound infection: 2 Patients with pain score greater than or equal to 16: 3 (10%) Median pain sum: 3 (1-8)			LOS: 1.2 (1-3) Wound infection: 0 Patients with pain score greater than or equal to 16: 2 (7%) Median pain sum: 4 (1-9)				
Pokala B 2019[56] Retrospective analysis of Vizient database Y N					Overall complications: 34 (1.7%) Post-op infection: 7 (0.4%) Post-op sepsis: 3 (0.2%) 7d readmission: 16	Overall complications: 851 (0.9%) Post-op infection: 133 (0.2%) Post-op sepsis: 53 (0.1%) 7d readmission: 998		

					(0.8%) 14d readmission: 26 (1.3%) 30d readmission: 37 (1.9%) Mortality: 1 (0.1%) LOS: 3.27 (2.72) Percentage of patients prescribed opiates: 97.2%	(1.0%) 14d readmission: 1415 (1.6%) 30d readmission: 1749 (2.0%) Mortality: 40 (<0.001%) LOS: 3.10 (2.22) Percentage of patients presribed opiates: 98.3%		
Rosemurgy A 2015[50] Retrospective analysis Y N								
Ross S 2014[53] Retrospective analysis Y N								
Spinoglio G 2011[37] Retrospective analysis N Y	LOS: 1.1 (0.3) Readmissions: 0 Major complications: 0 Wound infection: 0	LOS: 1.2 (0.7) Readmissions: 0 Major complications: 0						
Strosberg DS 2017[51] Retrospective analysis Y N					Readmissions: 5 (3.6%) LOS: 0 (0-4) Bile duct injury: 0 (0%) Bile leak: 3 (2.1%) Wound infection: 1 (0.7%) Reoperation: 2 (1.4%)	Readmissions: 4 (4.1%) LOS: 0 (0-8) Bile duct injury: 0 (0%) Bile leak: 1 (1%) Wound infection: 1 (1%) Reoperation: 1 (1%)		
Strosberg DS 2016[54] Retrospective analysis Y N					LOS: 0.55 60d readmission: 6 (4.23%) Bile duct injury: 0 Bile leak: 3 (2.11%) Reoperation: 2 (1.41%)	LOS: 1.35 60d readmission: 13 (11.4%) Bile duct injury: 0 Bile leak: 1 (0.88%) Reoperation: 2 (1.75%)		
Su WL 2016[38] Retrospective analysis N Y	LOS: 4.21 (0.72) Bile leakage: 0 (0%) Pain scale: 2.11 (0.76)	LOS: 4.13 (0.93) Bile leakage: 2 (3.17%) Pain scale: 3.98 (0.84)						

Wren SM 2011[29] Prospective analysis of SSRC with retrospective comparison to lap chole Y Y	Pain (at discharge): 2.5 (1.4) Pain (2-3 wks later): 0.67 (0.87)							
Teoh AY 2017[31] Prospective comparative study Not reported N	LOS: 1.4 (0.7) Morbidity rate: 14.3%			LOS: 1 (0) Morbidity rate: 0%				

Long-term Outcomes

Author **Year** **Population** **Study Design** **US (y/n)** **VA (y/n)**	**Long-Term Outcomes (>30d)** Readmissions Hernias GI-related complications Pain Quality of life % of patients that followed up at 6mo							
	Single-port Robot	**Single-port Lap**	**Multi-port Robot**	**Multi-port Lap**	**Unspecified Robot**	**Unspecified Lap**	**Specified combined single and multi-port Robot**	**Specified combined single multi-port Lap**
Abel SA 2019[32] Retrospective cohort Y N	Port-site hernia: 23 (8%)		Port-site hernia: 28 (10%)					
Aggarwal R 2020[22] Retrospective cohort N N								
Albrecht R 2017[17] Retrospective (matched-pair analysis) N N								
Altieri MS 2016[45] SPARCS database Prospective cohort								

Y N								
Aragon RJ 2014[44] Prospective observational study Y N								
Autin RL 2015[39] Retrospective analysis Y N	Port site hernias: 3 (11.1%)	Port site hernias: 6 (22.2%)						
Balachandran B 2017[23] Retrospective cohort Y N	Umbilical incisional hernia: 27 (6.5%)			Umbilical incisional hernia: 5 (1.9%)				
Buzad FA 2013[33] Prospective cohort with historically (retrospective) matched-pairs Y N								
Calatayud D 2012[116] Retrospective analysis Y N								
Chung PJ 2015[24] Retrospective cohort Y N								
Eid JJ 2020[21] Retrospective cohort Y N								
Farnsworth J 2018[46] Observational (prospectively collected registry) Y N								
Farukhi MA 2017[52] Case control retrospective analysis Y N								

Gonzalez AM 2013[34] Retrospective cohort Y N								
Grochola LF 2018[13] RCT No (Switzerland) No	Incisional hernia: 6.7% (2) HRQoL (Preop, median): 107(62-135) HRQoL (1mo postop, median): 123 (83-140) HRQoL (12mo postop, median): 123 (105-141) Body image (1mo postop, median): 37 (24-40) Body image (12mo postop, median): 35.5 (20-40)	Incisional hernia: 6.7% (2) HRQoL (Preop, median): 109.5 (39-131) HRQoL (1mo postop, median): 120 (55-142) HRQoL (12mo postop, median): 128 (94-143) Body image (1mo postop, median): 38 (19-40) Body image (12mo postop, median): 39 (22-40)						
Gustafon M 2016[36] Observational (retrospective analysis of prospective database) Y N	Incisional hernia: 1 (2.6%)	Incisional hernia: 2 (4.5%)						
Hagen ME 2018[25] Restrospective cohort, matched pair N N	Operation for incisional hernia: 7 (7.1%)			Operation for incisional hernia: 0				
Hagen ME 2017[30] Retrospective, case-matched analysis Y N	Incisional hernia: 6			Incisional hernia: 0				
Hawasli A 2016[55] Observational (retrospective) Y N								
Heemskerk J 2014[14] Prospective Randomized Trial								

N N								
Higgins RM 2017[61] Surgical Profitability Compass Procedure Cost Manager System Database Retrospective analysis Y N								
Jang EJ 2019[40] Retrospective analysis N N								
Kaminski JP 2014[58] NIS dataset Retrospective analysis Y N								
Kane WJ 2020[57] Retrospective Cohort Y N					90d readmission: 0 (0%)	90d readmission: 43 (4.1%)		
Khorgami Z 2019[49] NIS Retrospective analysis Y N								
Kudsi OY 2017[15] Randomized controlled trial Mixed (7 institutions in US, 1 in Greece) N								
Lee EK 2017[26] Retrospective analysis N N								
Lee SR 2019[27] Retrospective analysis N N								

Lee JH 2018[41] Retrospective analysis Y N	Incisional hernia: 1	Incisional hernia: 1						
Lescouflair T 2014[42] Retrospective review of prospectively maintained database Y N								
Li YP 2017[28] Retrospective analysis N N	Incisional hernia: 1			Incisional hernia: 2				
Main WPL 2017[18] Retrospective analysis Y N								
Mitko J 2016[20] Retrospective analysis Y N								
Moore MD 2016[43] Retrospective analysis Y N								
Pietrabissa A 2016[16] Prospective, randomized, double-blind trial N N	Incisional hernia: 1		Incisional hernia: 0					
Pokala B 2019[56] Retrospective analysis of Vizient database Y N								
Rosemurgy A 2015[50] Retrospective analysis Y N								
Ross S 2014[53] Retrospective analysis Y N								

Spinoglio G 2011[37] Retrospective analysis N Y								
Strosberg DS 2017[51] Retrospective analysis Y N					Port site hernia: 0	Port site hernia: 0		
Strosberg DS 2016[54] Retrospective analysis Y N								
Su WL 2016[38] Retrospective analysis N Y								
Teoh AY 2017[31] Prospective comparative study Not reported N	Quality of life assessment score: 22.9 (2.7)			Quality of life assessment score: 24.4 (3.1)				
Wren SM 2011[29] Prospective analysis of SSRC with retrospective comparison to lap cholecystectomy Y Y								

INGUINAL HERNIA REPAIR

Author **Year** **Population** **Study Design** **US** **VA** **# Institutions/ Surgeons** **Propensity Matching (y/n)** **Total N**	**Patient Characteristics Preop** Total patients (N) Age, mean yr (SD) Race/Ethnicity NH-White, % NH-Black, % NH-Asian, % NH-Other/Unknown, % Hispanic, % Male, % BMI, mean (SD) ASA ≥ 3, % Diabetes, % Smokers, % Hernia characteristics Elective surgery, % Primary hernia, % Unilateral, % Pain, %			**Intraoperative Outcomes** OR time, min (SD) EBL, mL (SD) Transfusions, % Complications, % Conversion To Open, % To Lap, % Mesh repair, % Surgical approach TEP, % TAPP, % Concurrent procedures, type, % *Italicized text indicates that an outcome has been separately reported by laterality*			**Short-Term Outcomes (≤30d)** LOS, mean (SD) Readmissions, % Reoperations, % ED visits, mean (SD) Complications, % SSO, % Seroma/Hematoma, % Enterotomy, % Pain, % Narcotic use, % Return to work, % Retention, % Other, % Mortality, % *Italicized text indicates that an outcome has been separately reported by laterality*			**Long-Term Outcomes (>30d)** Follow-up at 1 year, % Length of follow-up, mean (SD) Readmissions, % Mesh infection, % Pain, % Recurrence, % QOL			**Primary Multi-Variate Findings**	**Comments**
	Robot	**Lap**	**Open**	**Robot**	**Lap**	**Open**	**Robot**	**Lap**	**Open**	**Robot**	**Lap**	**Open**		
Abdelmoaty, 2018[75] Robot vs lap Retrospective US 32/164 (115 lap; 49 robot) n N=2405	N=734 Elective 100% Primary 86.2% Unilateral 100%	N=1671 Elective 100% Primary 88% Unilateral 100%		OR Skin-skin 87 Room time 125 Conversion 5.4% (open) Concurrent 0%	OR Skin-skin 56 Room time 90 Conversion 5.3% (open) Concurrent 0%		LOS (d) 0.26	LOS (d) 0.25					Robotic significantly longer OR time (p<0.001 for both in-room and cut-to close)	
AlMarzooqi, 2019[71] Robot vs lap vs open Prospective (AHSQC) US n N=4613	N=847 Age 59.0 Male 91.0% BMI 27.0 Elective 100% Primary 100% Unilateral 100%	N=1841 Age 60.0 Male 93.0% BMI 26.0 Elective 100% Primary 100% Unilateral 100%	N=1925 Age 64.4 Male 90.9% BMI 25.9 Elective 100% Primary 100% Unilateral 100%	Mesh 100% TEP 1% TAPP 99%	Mesh 100% TEP 67% TAPP 33%	Mesh 92%	SSO 1.4% Seroma/ hematoma 2.7%	SSO 3.4% Seroma/ hematoma 5.8%	SSO 4.1% Seroma/ hematoma 13.9%	1-yr F/U 6.0% F/U 1y Recur 2.0% QOL* 12.9	1-yr F/U 9.4% F/U 1y Recur 4.0% QOL* 10.3	1-yr F/U 7.2% F/U 1y Recur 8.7% QOL* 12.1		*Calculated based on a median; 30-day EuraHS QOL score Data pooled from subgroup analyses (by procedure type)
Bittner, 2018[12] Robot vs lap vs open	N=83 Age	N=83 Age					Pain (scale) 4.0 (0.3)	Pain (scale) 4.4 (0.3) Narc*		1-yr F/U n=83 F/U (mo)	1-yr F/U N=83			*Days to no Rx

Random sample from web-based research panel US na/na y N=166 (526 unmatched)	54.4 (11.0) Male 97.6% Pain (Rx) 30.1% Pain (scale) 5.4 (0.4)	57.5 (12.3) Male 100% Pain (Rx) 25.3% Pain (scale) 5.8 (0.3)					Narc* 9.4 (1.5) RTW (d) 17.8 (2.1)	11.6 (1.7) RTW (d) 17.9 (2.8)		5.7 (0.3) Pain (scale) 1.5 (0.3)	F/U (mo) 6.0 (0.3) Pain (scale) 1.1 (0.2)			
Bittner, 2018[12] **Robot vs** lap vs **open** Random sample from web-based research panel US na/na y N= 170 (526 unmatched)	N=85 Age 53.2 (11.9) Male 97.6% Pain (Rx) 31.8% Pain (scale) 5.6 (0.3)		N=85 Age 56.2 (12.0) Male 98.8% Pain (Rx) 29.4% Pain (scale) 5.8 (0.4)				Pain (scale) 4.1 (0.3) Narc* 9.4 (1.4) RTW (d) 17.0 (2.0)		Pain (scale) 5.6 (0.3) Narc* 10.6 (1.2) RTW (d) 21.7 (2.4)	1-yr F/U n=85 F/U (mo) 5.7 (0.3) Pain (scale) 1.6 (0.3)		1-yr F/U n=85 F/U (mo) 6.7 (0.3) Pain (scale) 2.2 (0.3)	Postop pain (1 wk) significantly higher on open vs robot (p<0.01)	*Days to no Rx Pain rating = APGP score
Charles, 2018[68] Robot vs lap vs open Prospective (NSQIP) US VA 1/10 (2 robotic, 8 lap, 4 open) n N=510	N=69 Age* 52 [39-62] White 87% Male 85.5% BMI* 24.9 [22.9-28.7] ASA 14.5% Diabetes 1.5% Smokers 23.2% Primary 100% Unilateral 100%	N=241 Age* 57 [45-67] White 88.4% Male 88.8% BMI* 25.8 [23.1-28.4] ASA 15.4% Diabetes 0.4% Smokers 18.3% Primary 100% Unilateral 100%	N=191 Age* 56 [48-67] White 85.9% Male 91.6% BMI* 25.1 [23.2-27.8] ASA 28.8% Diabetes 1.6% Smokers 28.3% Primary 100% Unilateral 100%	OR Room time* 105 [76-146] Txf 0% Mesh 100% TAPP 100% Concurrent 1.5%	OR Room time* 81 [61-13] Txf 0.4% Mesh 100% TAPP 100% Concurrent 0.8%	OR Room time* 71 [56-88] Txf 0% Concurrent 1.6%	Readmit 0% Comp 2.9% SSO 2.9% Other 0% Mortality 0%	Readmit 2.1% Comp 3.3% SSO 0% Other 1.7% Mortality 0%	Readmit 3.7% Comp 5.2% SSO 0.5% Other 2.6% Mortality 0%	Recur** 0%	Recur** 0%	Recur** 0%	Total operating time greater for robot (p<0.001)	*Median [IQR] **30-day
Gamagami, 2018[69]	N=444 (652		N=444 (602	OR Skin-skin		OR Skin-skin	LOS (d) 3.0 (2.6)		LOS (d) 5.7 (6.8)				30-day postoperative	*Postop transfusion

Robot vs open Retrospective US 6/7 y N=888 (1,254 unmatched)	unmatched) Age 55.8 (15.9) Male 89.4% BMI 26.8 (4.7) ASA□3 25.2% Primary 87.4% Unilateral 84.5%		unmatched) Age 56.4 (16.0) Male 90.3% BMI 27.0 (5.0) ASA□3 27.3% Primary 87.4% Unilateral 84.0%	74.0 (30.1) Txf* 0.5% Comp 0.5% Conversion 1.4% (open) Mesh 100% TAPP 100% Concurrent 14.6%		46.6 (23.0) Txf* 0.2% Comp 0% Mesh 100% Concurrent 13.7%	Readmit 2.5% Reop 0.5% Comp** 7.2% SSO 0.2% Seroma/ hematoma 1.1% Retention 2.3% Pain 0.7% Other 3.4% Mortality 0%		Readmit 2.3% Reop 1.6% Comp** 9.5% SSO 1.6% Seroma/ hematoma 2.3% Retention 0.5% Pain 2.5% Other 3.2% Mortality 0.2%				complications higher in open (p=0.047) Shorter OR time (skin to skin) in open (p<0.0001) Lower inpatient LOS in robot (p=0.043)	**Post-op complications stratified between "prior to d/c" and "post-d/c, prior to 30 days". Pooled in this table.
Holcomb, 2019[84] Robot vs open Prospective (AHSQC) US na/na n N=1170	N=540 Age 60 [48-70] DM 8% Elective 100% Primary 100%		N=630 Age 65 [55-73] DM 11% Elective 100% Primary 100%	TAPP 100%			Readmit 1% Comp 5% SSO 0.4% Seroma/ hematoma 1.6%		Readmit 1% Comp 5% SSO 1.6% Seroma/ hematoma 1.4%	Recur* 0.2%		Recur* 0.0%		*30-day recurrence
Huerta, 2019[70] Robot vs lap vs open Retrospective US VA 1/3 (1 surgeon per approach) n N=1299	N=71 Age 59.9 (12.5) White 69.0% Black 22.5% Hispanic 7.0% Male 100% BMI 27.5 (5.2) ASA 2.4 (0.5) DM 15.5% Smoking 33.8%	N=128 Age 58.3 (12.4) White 73.4% Black 19.5% Hispanic 3.1% Male 100% BMI 26.3 (4.1) ASA 2.6 (0.6) DM 10.9% Smoking 40.6% Primary 49.9%	N=1100 Age 61.3 (12.8) White 73.7% Black 20.5% Hispanic 5.2% Male 99.9% BMI 26.6 (4.3) ASA 2.6 (0.6) DM 12.7% Smoking 32.6% Primary	OR 117.5 (61.8) Mesh 100% TAPP 100% Concurrent 11.3%	OR 78.4 (27.1) Mesh 100% TEP 100% Concurrent 11.7%	OR 65.5 (26.1) Mesh 100% Concurrent 0.4%	LOS 0.3 (0.8) Comp 18.2% SSO 0% Seroma/ hematoma 2.8% Retention 5.6% Pain 2.8% Ileus 0% Other 7.0%	LOS 0.11 (0.5) Comp 21.2% SSO 0.8% Seroma/ hematoma 1.6% Retention 5.5% Pain 7.0% Ileus 0% Other 6.3%	LOS 0.24 (1.1) Comp 7.9% SSO 0.8% Seroma/ hematoma 2.6% Retention 1.8% Pain 0.8% Ileus 0.7% Other 1.2%	F/U (y) 2.4 (0.8) Pain 14.1% Recur 5.6%	F/U (y) 3.9 (1.8) Pain* 9.4% Recur 3.9%	F/U (y) 5.6 (3.6) Pain* 1.5% Recur 1.7%	OR time for robot sig longer than both open and lap (p<0.001 for both) Robot significantly more inguinodynia than open (p<0.001) Robot significantly more urinary retention than open (p=0.03)	*Inguinodynia

	Primary 74.6% Unilateral 40.8%	Unilateral 19.0%	99.2% Unilateral 92.7%										Robot had significantly more overall complications than open ($p<0.001$) Recurrence higher in robot vs open ($p<0.02$) Open had a longer f/u time than both lap and robot ($p<0.001$)	
Janjua, 2020[77] Robot vs lap vs open Prospective database (AHA-HCUP) US na/na y N=35916 **Pooled**	N=1480 Age >70: 19% Race: 79% white 8% AA 7% Hispanic 1% Asian 5% other Male: 95% CCS ≥1: 91% Elective: 75% Unilateral: 75%	N=7011 Age >70: 42% Race: 76% white 8% AA 10% Hispanic 2% Asian 4% other Male: 81% CCS ≥1: 42% Elective: 35% Unilateral: 68%	N=27425 Age >70: 46% Race: 70% white 12% AA 12% Hispanic 2% Asian 4% other Male: 85% CCS ≥1: 49% Elective: 22% Unilateral: 92%				LOS: 2.22 (2.85) *U/L: 2.2 (2.8)* *B/L: 2.3 (3.1)*	LOS: 3.27 (4.74) *U/L: 3.5 (5.2)* *B/L: 2.8 (3.6)*	LOS: 4.22 (6.22) *U/L: 4.3 (6.3)* *B/L: 4 (5.3)*				LOS for robot significantly decreased vs lap vs open ($p<0.0001$)	
Janjua, 2020[77] **Matched**	N=1480	N=2960	N=2960				LOS: 2.22 (2.85)	LOS: 3.6 (5.5)	LOS: 5.0 (8.2)				LOS for robot significantly decreased vs lap vs open ($p<0.0001$)	
Kakaishvili, 2018[72] Robot vs lap vs open Retrospective Israel 1/na	N=24 Unilateral 29.2%	N=16 Unilateral 50%	N=97 Unilateral 87.6%	OR 92.5	OR 79.0	OR 44.0	LOS 1.0 Pain* 0 Narc** 1.0	LOS 1.0 Pain* 2.0 Narc** 1.5	LOS 1.0 Pain* 5.0 Narc** 3.0				*Median VAS score **Analgesia (per day) Postoperative VAS level significantly	

n N=137													higher in open (p<0.001) Robot had a longer OR time than lap or open (p<0.001)	
Khoraki 2019[78] Robot vs lap Retrospective cohort US 1/4 n N=183	N=45 Age: 49.6 (13.7) Male: 93.3% BMI: 27.5 (5.8) ASA ≥ 3: 20% DM: 4.4% Primary: 88.9% Unilateral: 82.2%	N=138 Age: 50 (13.3) Male: 96.4% BMI: 26.2 (3.6) ASA ≥ 3: 8.7% DM: 10.1% Primary: 95.7% Unilateral: 70.3%		OR time: 116 (36) U/L: 110 (35) B/L: 143 (33) Conversion to open: 0% Mesh: 100% TAPP: 100% TEP: 0%	OR time: 95 (44) U/L: 88 (37) B/L: 114 (54) Conversion to open: 0.7% Mesh: 100% TAPP: 0% TEP: 100%		LOS: 0.13 [0-2] Readmit: 3 (6.7%) Reop: 3 (6.7%) Comp: 13 (28.9%) SSI: 1 (2.2%) Seroma: 5 (11.1%) Hematoma: 1 (2.2%) Retention: 2 (4.4%) SBO: 2 (4.4%) Ileus: 1 (2.2%)	LOS: 0.04 [0-1] Readmit: 1 (0.7%) Reop: 0 (0%) Comp: 25 (18.1%) SSI: 0 (0%) Seroma: 16 (11.6%) Hematoma: 1 (0.7%) Retention: 7 (5.1%) SBO: 0 (0%) Ileus: 0 (0%)		F/U: 30 d	F/U: 30 d		Overall OR time longer for robot (p<0.01) and unilateral repairs (p<0.01); bilateral repairs not significant (p=0.06) No difference in conversion to open (p=0.57) Similar LOS (p=0.16), complications (p=0.14); increased reoperations with robot (p=0.01) and 30-day readmission with robot (p=0.04)	
Knott, 2017[80] Robot vs lap vs open Prospective (Truven MarketScan) na/na n N=75,981	N=262 Primary 100%	N=25,433 Primary 100%	N=50,286 Primary 100%							F/U 1 y Recur 2.7%	F/U 1 y Recur 3.5%	F/U 1 y Recur 3.9%	Rate of repeat IHR was significantly lower in lap vs open [HR 0.90 (CI 0.83-0.98), p=0.019] and trended lower in RAS vs open [HR 0.69 (CI 0.33-1.44), p=0.32]	

Kolachalam, 2017[66] Robot vs open Retrospective US 6/7 y N=188	N=95 Age 53.5 (11.9) Male 91.6% BMI 33.6 (3.8) ASA 35.8% Unilater al 87.4%		N=93 Age 54.0 (14.5) Male 88.2% BMI 34.2 (5.2) ASA 33.3% Unilateral 86.0%	OR Skin-skin 82.9 (35.7) Txf 0% Conversion 3.2% (open) Comp 1.1% Mesh 100% TAPP 100% Concurrent 17.9%		OR Skin-skin 51.5 (20.9) Txf 0% Comp 0% Mesh 100% Concurre nt 19.4%	LOS (d) 1.9 (0.9) Readmit 1.0% Reop 0.0% Comp 3.2% SSO 0% Seroma/ Hematoma 1.1% Retention 2.1% Other 0%		LOS (d) 4.4 (3.6) Readmit 2.2% Reop 2.2% Comp 10.8% SSO 3.2% Seroma/ Hematoma 2.2% Retention 1.1% Other 4.3%				Open had more postop complications (p=0.047) Robot had longer OR time (p<0.001)	Propensity matched for BMI >= 30 group
Kosturakis, 2018[67] Robot vs open Retrospective US VA 1/na n N=200	N=100 Age 57.2 (1.3) Male 100% BMI 27.8 (0.5) ASA 35% Primary 78% Unilater al 41% Pain (scale) 0		N=100 Age 63.5 (1.1) Male 99% BMI 26.2 (0.5) ASA 62% Primary 87% Unilateral 93% Pain (scale) 0	OR 109.7 (3.6) *Unilateral* *90.5 (5.0)* *Bilateral* *121.9 (4.9)* Comp 0% Mesh 100% TAPP 100% Concurrent 9%		OR 83.7 (2.6) *Unilateral* *80.2* *(2.2)* *Bilateral* *121.5* *(18.3)* Comp 0% Concurre nt 5%	ED 6% Comp 21% SSO 3% Pain (scale) 0 Pain (visits) 0% Narcotic 5% Retention 18% Other 0%		ED 11% Comp 22% SSO 7% Pain (scale) 0 Pain (visits) 9% Narcotic 12% Retention 13% Other 2%	Pain (referral) 0% Recur 4%		Pain (referral) 1% Recur 4%	OR times longer for robot (p<0.0001) More post-op visits for pain in open group (p=0.003)	
Kudsi, 2017[74] Robot vs lap Retrospective US 1/1 n N=275	N=118 Age 58.8 (15.4) Male 85.6% BMI 28.4 (5.0) ASA□3 28.0% Elective 97.5% Primary 93.2% Unilater al	N=157 Age 55.1 (14.8) Male 94.9% BMI 27.1 (4.9) ASA□3 19.9% Elective 99.4% Primary 91.1% Unilateral 76.4%		OR Skin-skin 69.1 (35.1) *Unilateral* *64.5 (35.6)* *Bilateral* *80.2 (31.7)* Comp 0 Conversion 0% Mesh 100% TAPP 100%	OR Skin-Skin 69.1 (26.3) *Unilateral* *63.3 (23.6)* *Bilateral* *88.3 (26.1)* Comp 0.6% Conversion 0.6% Mesh 100% TEP 100%		Readmit 3.4% Comp[*] 6.8% SSO 0% Seroma/ hematoma 1.7% Retention 1.7% Other 3.4%	Readmit 1.9% Comp[*] 5.1% SSO 0% Seroma/ hematoma 1.9% Retention 1.3% Other 1.3%		1-yr F/U 85.6% F/U 1 y Pain[**] 0.8% Recur 0%	1-yr F/U 100% F/U 1 y Pain[**] 0.6% Recur 0.6%			[*]3-month complications [**]Inguinodyni a

	70.3%													
Lammers, 2019[83] Robot vs lap vs open Retrospective US 1/na y N=277	BMI 31	BMI 26	BMI 27	OR 146	OR 86	OR 75	Readmit 0%	Readmit 1.2%	Readmit 2.4%	F/U 30 d	F/U 30 d	F/U 30 d	Robot had significantly longer OR times (p<0.001) Higher readmission in open group (p=0.03)	
Macias, 2017[81] Robot vs lap Retrospective US 2/1 n N=55	N=21	N=34		OR 71.2	OR 54.2		LOS (min)* 113.4	LOS (min)* 144.4		Pain** 24%	Pain** 3%		Mean OR time longer for robot (p=0.001) Higher prevalence of inguinodynia in robot group	*Recovery room time **Inguinodynia
Muysoms, 2018[73] Robot vs lap Prospective (lap data from previous published studies) Belgium 1/1 n N=112 **Pooled**	N=49 Age 58.8 Male 98.0% BMI 25.0 Unilateral 69.4% QOL* 24 [14-37] Pain 7 [4-13]	N=63 Age 57.7 Male 96.8% BMI 24.4 Unilateral 59.5% QOL* 17 [11-28] Pain 4 [2-9]		OR Skin-skin 61.3 Room time 101.7 Comp 0% Conversion 0% Mesh 100% TAPP 100%	OR Skin-skin 59.3 Room time 95.1 Comp 0% Conversion 0% Mesh 100% TAPP 100%		Comp 24.5% Seroma/ hematoma 14.3% Retention 10.2%	Comp 15.9% Seroma/ hematoma 11.1% Retention 4.8%		F/U (wk) 4 (100%) QOL** 4 [1-12] Pain: 1 [0-3]	F/U (wk) 4 (100%) QOL** 6 [3-14], Pain: 2 [0-5]			*EuraHS **EuraHS 1 mo postop Median [IQR] Examined learning curve (single surgeon without clinical experience with robot)
Muysoms, 2018[73] Robot vs lap **Unilateral**	N=34 Age 60.4 (16.5) Male 97.1% BMI 25 (3.4)	N=22 Age 59.0 (11.8) Male 90.9% BMI 24 (3.0)		OR Skin-skin 54 (16) Room time 94 (17) Concurrent 3%	OR Skin-skin 45 (11) Room time 79 (10) Concurrent 5%		Comp 23.5% Seroma/ hematoma 15% Retention 9%	Comp 9% Seroma/ hematoma 9% Retention 0%						
Muysoms, 2018[73] Robot vs lap **Bilateral**	N=15 Age 55.3 (12.5)	N=41 Age 57.0 Male		OR Skin-skin 78 (16) Room time	OR Skin-skin 67.0 Room time		Comp 26.6% Seroma/ hematoma	Comp 19.5% Seroma/ hematoma						

	Male 100% BMI 25 (2.1) Primary 86.7%	100% BMI 24.6 Primary 100%		119 (15)	101.8		13.3% Retention 13.3%	12.2% Retention 7.3%						
Pokala, 2019[82] Robot vs lap vs open Prospective (Vizient) US na/na n N=3,547	N=594 White 81.5% Black 9.4% Other 9.1% Male 95.3% Elective 100%	N=540 White 77.0% Black 11.9% Other 11.1% Male 80.4% Elective 100%	N=2413 White 75.8% Black 12.1% Other 12.2% Male 84.1% Elective 100%				LOS (d)* 1.8 [1.6] Readmit 0.8% Comp 0.7% SSI 0.0% Narcotic** 93.8% (7.6, 1.5) Mortality 0.2%	LOS (d)* 2.2 [2.1] Readmit 2.2% Comp 4.4% SSI 0.6% Narcotic** 93.1% (9.7, 1.7) Mortality 0.2%	LOS* 3.6 d [4.1] Readmit 3.6% Comp 3.9% SSI 8.3% Narcotic** 96.0% (24.8, 2.3) Mortality 0.2%	F/U 30 d	F/U 30 d	F/U 30 d	Overall complications lower for robot (p<0.05 vs open and lap) Postop infection + LOS significantly higher in open (p<0.05 for lap and robot)	*Median [IQR] **Pain quantified by: % patients prescribed opiates (mean units used, mean days used) Direct cost 9431 (5490) vs 6502 (4005) vs 8837 (14353) Open more expensive than lap (p<0.05) Robot more expensive than lap (p<0.05)
Prabhu 2020[63] Robot vs lap RCT US 6/na n/a N=102	N=48 Age: 56.1 (14.1) Race: 83.3% white, 4.2% Hispanic, 10.4% AA, 0% Asian, 2.1% other Male: 91.6% BMI: 24.9 (3.24) DM: 7.4% Tob: 11.3%	N=54 Age: 57.2 (13.3) Race: 83.3% white, 1.8% Hispanic, 11.1% AA, 1.8% Asian, 0% other Male: 88.9% BMI: 26.9 (4.42) DM: 4.2% Tob: 6.2% Primary: 94.4% Unilateral: 100% Pain*: 18.8		Skin-skin time: 75.5 {59.0-93.8} Conversion to lap: 2.1% TAPP: 100%	Skin-skin time: 40.5 {29.2-63.8} TAPP: 100%		LOS (hrs): 5.75 {5-7} Readmit: 4 (8.3%) Comp: 8 (16.7%) SSI: 0% Seroma: 6 (12.5%) Hematoma: 1 (2.1%) Retention: 1 (2.1%) 1-w pain*: +5.53 1-m pain*: -7.00	LOS (hrs): 5.11 {4-7} Readmit: 2 (3.8%) Comp: 5 (9.3%) SSI: 2 (3.7%) Seroma: 3 (5.6%) Hematoma: 0 (0%) Retention: 1 (1.8%) 1-w pain*: +4.60 1-m pain*: -7.92		F/U: 30 d % F/U: 93.8%	F/U: 30 d % F/U: 98.1%		Greater skin-skin time in robot group (p<0.001) Similar LOS (p=0.424) readmission rate (p=0.420), and overall complication rate (p=0.374) No differences in change in VAS score from baseline at 1-week (p=0.86) and 30-d (p-0.85)	{} = IQR * Visual Analog Scale (VAS); follow-up pain assessments reflect score change from baseline

	Primary: 89.4% Unilateral: 100% Pain*: 15.2													
Sheldon 2019[79] Robot vs lap vs open Retrospective cohort US 1/na n N=173	N=49 Age: 38.2 (11) Male: 87.8% Primary: 100% Unilateral: 61.2%	N=34 Age: 40.8 (12) Male: 91.2% Primary: 100% Unilateral: 58.9%	N=90 Age: 39.7 (14) Male: 97.8% Primary: 100% Unilateral: 98.9%	TAPP: 100% TEP: 0%	TAPP: 0% TEP: 100%	Mesh: 100%	Pain (MME): 208.4 (123.6) *U/L: 205.4 (139.5)* Narc: 98.2% *U/L: 96.7%*	Pain (MME): 229.4 (126.2) *U/L: 198.7 (116.1)* Narc: 97.2% *U/L: 95.0%*	Pain (MME): 230.4 (122.3) *U/L: 230.5 (123.2)* Narc: 98.5% *U/L: 97.8%*	F/U: 3 mo Repeat Rx: 8.2% *U/L: 6.7%*	F/U: 3 mo Repeat Rx: 8.8% *U/L: 5.0%*	F/U: 3 mo Repeat Rx: 10.0% *U/L: 9.0%*	Equal opioid use in all groups at discharge (p=0.962) and at follow-up requiring repeat Rx (p=0.935); same for laterality-controlled subanalysis (p=0.803 and p=0.807)	MME = morphine milligram equivalents
Switzer, 2019[64] Robot vs lap Prospective (AHSQC) US na/na n N=148	N=33 Elective 100% Unilateral 100% Pain 10 QOL* 33 (pain 10, restriction 17, cosmetic 6)	N=115 Elective 100% Unilateral 100% Pain 6 QOL* 20 (pain 6, restriction 9, cosmetic 5)					Comp 15%	Comp 9%		F/U 6 mo Readmit 3% Mesh inf 0% Pain 0 Recur 0% QOL* 0	F/U 6 mo Readmit 0% Mesh inf 0% Pain 0 Recur 0% QOL* 0		No significant outcome differences	*EuraHS score
Waite, 2016[65] Robot vs lap Retrospective US 1/1 n N=63	N=39 Age* 58.1 {21-80} Male 97.4% BMI* 27.5 {23.0-35.9} Unilateral 74.4%	N=24 Age* 57.5 {43-72} Male 100% BMI* 27.6 {21.0-33.3} Unilateral 75.0%		OR Skin-skin* 77.5 {n/a} *Unilateral 67.6* *Bilateral 106.2* Room time 109.3 *Unilateral 100.0* *Bilateral 135.4* Mesh 100% TAPP 100%	OR Skin-skin* 60.7 {45-102} *Unilateral 55.0* *Bilateral 77.8* Room time 93.0 *Unilateral 87.7* *Bilateral 108.7* Mesh 100% TAPP		LOS (min) 218.4 *Unilateral 209.4* *Bilateral 244.4* Pain** 2.5 *Unilateral 2.2* *Bilateral 3.5*	LOS (min) 226.5 *Unilateral 216.3* *Bilateral 256.8* Pain** 3.8 *Unilateral 3.4* *Bilateral 5.1*					Significantly longer OR time for robotic (p=0.001) Robotic surgery patients spent less time in recovery (p=0.033 for bilateral surgery, p=0.149 for unilateral	*Mean {Range} **Median of scale (1-10) Cost data (no sig diff) Ave direct cost: 3216 vs 3479 (lap vs robot)

				Concurrent 12.8%	100% Concurrent 0%								surgery) with less reported pain (p=0.062 for unilateral, p=0.090 for bilateral)	
Zayan, 2019[76] Robot vs lap Retrospective US 1/3 n N=105	N=37 Age 53.9 (49.1–58.6) Male 100% BMI 27.4 (25.3–29.4) DM 5.4% Smoker 27.0% Elective 100% Primary 81.1% Unilateral 48.6% QOL* 29.7 (19.3–39.1)	N=68 Age 52.7 (49.2–56.1) Male 86.8% BMI 26.1 (25.1–27.1) DM 7.4% Smoker 11.8% Elective 100% Primary 91.2% Unilateral 76.5% QOL* 19.4 (11.4–26.9)		OR 120 (105-135) Mesh 100% TEP 0% TAPP 100% Concurrent 5.4%	OR 58 (54-63) Mesh 100% TEP 52.9% TAPP 47.1% Concurrent 0%		LOS (h) 15.5 (10.0–20.8) QOL* 10.7 (2.1–18.3)	LOS (h) 9.6 (8.3–11.0) QOL* 10.2 (5.5–14.3)		F/U (mo) 14.1 (13.1–15.0) Recur 0.0% QOL* 8.4 (2.6–14.0)	F/U (mo) 15.5 (14.7–16.3) Recur 5.9% QOL* 5.1 (2.0–7.4)		Significantly longer OR time for robotic (p<0.001)	*Carolinas Comfort Scale (CCS)

VENTRAL HERNIA REPAIR

Author, Year Population Study Design US (y/n) VA (y/n) #Institutions/ Surgeons Propensity Matching (y/n) Total N	**Patient Characteristics Preop** Total N Age, mean yr (SD) Race/Ethnicity NH-White, % NH-Black, % NH-Asian, % NH-Other/Unknown, % Hispanic, % Male, % BMI, mean (SD) ASA class, mean (SD) Diabetes, % Smokers, % Hernia characteristics Elective surgery, N (%) Hernia area, cm^2 (SD) Midline hernia, N (%) Recurrent hernia, N (%)			**Intraoperative Outcomes** OR time, min (SD) EBL, mL (SD) Transfusions, % Complications, % Conversion To Open, % To Lap, % Mesh repair, % Fascial closure, % Concurrent procedure, %			**Short-Term Outcomes (<=30d)** Readmissions, N (%) Reoperations, N (%) ED visits, mean (SD) LOS, mean days (SD) Complications, N (%) SSI, N (%) SSO, N (%) Seroma, N (%) Hematoma, N (%) Enterotomy, N (%) Pain, N (%) Narcotic use, N (%) Return to work, N (%) Mortality, N (%) Urinary retention, N (%) Other, N (%) Ileus, N (%)			**Long-Term Outcomes (>30d)** Follow-up at 1 year, % Length of follow-up, mean (SD) Readmissions, N (%) Mesh infection, N (%) Pain, N (%) Recurrence, N (%) QOL			**Primary Multi-Variate Findings**	**Comments**
	Robot	Lap	Open	Robot	Lap	Open	Robot	Lap	Open	Robot	Lap	Open		
Abdalla, 2017[85] Robot vs lap VHR RCT N (Brazil) N 1/NR N N=38 Abstract only	N=19	N=19					Mortality: 0	Mortality: 1 (5.26%)		F/U length: >1 yr Recur: 2 (10.53%)	F/U length: >1 yr Recur: 4 (21.05%)		Trend toward better QOL improvement and improved abdominal wall function in robot group Similar outcomes and morbidities	Cost
Altieri, 2018[99] Robot vs lap VHR Prospective cohort (NY Statewide Planning and Research Cooperative System) Y N NR/NR	N=679 Race: 75.11 % white, 12.37 % AA, 0.44% Asian, 4.57% Hispanic, 7.51% other	N=20896 Race: 65.12% white, 12.79% AA, 1.02% Asian, 11.79% Hispanic, 9.28% other					Readmit: 63 (9.28%) Reop: ED: 98 (14.43%) LOS: 2.19 (6.31) Complication: 137 (20.18%)	Readmit: 1058 (5.06%) Reop: ED: 2185 (10.46%) LOS: 4.32 (18.04) Complication: 2206 (10.56%)		F/U length: 30 d	F/U length: 30 d		Higher readmission (p<0.0001), ED revisit (p<0.0001), complication rate (p<0.0001), and longer LOS (p=0.0023) in robot group	

Y (see row below) N=21575	Male: 86.89 % BMI>30: 25.77 % DM: 19.00 %	Male: 44.55% BMI>30: 11.27% DM: 11.23%												
Altieri, 2018[99] N=1356 Propensity score matched	N=678	N=678					Readmit: ED: LOS: Complication:	Readmit: ED: LOS: Complication:					Propensity score matched, no difference in 30-day readmission (p=0.2760), ED revisit (p=0.2043); shorter LOS (-1 day, p<0.0001) and decreased complication rate (-0.0575 risk difference, CI -0.1023- -0.0128, p=0.0134)	
Armijo, 2018[104] Robot vs lap vs open VHR Prospective cohort (Vizient) Y N NR/NR N N=46799	N=465 Age: 59 (13.1) Male: 40.2% ASA: NR ("major" illness: 15.3%)	N=6829 Age: 57 (13.2) Male: 60.8% ASA: NR ("major" illness: 6.9%)	N=39505 Age: 57 (13.3) Male: 58.3% ASA: NR ("major" illness: 18.8%)				Readmit: 3.87%, CI 2.31-6.05 LOS: 2 (IQR 1-4) Complication: 7.3%, CI 5.1-10.0 SSI*: 1.72%, CI 0.75-3.36 Narc**: 95.8%, 19.5, 2.8 Mortality: 0.43%, CI 0.05-1.54	Readmit: 2.86%, CI 2.47-3.28 LOS: 3 (IQR 2-4) Complication: 3.5%, CI 3.1-4.0 SSI*: 0.67%, CI 0.49-0.90 Narc**: 96.3%, 20.8, 2.6 Mortality: 0.16%, CI 0.08-0.29	Readmit: 7.55%, CI 7.29-7.81 LOS: 5 (IQR 3-8) Complication: 11.4%, CI 11.1-11.75 SSI*: 2.83%, CI 2.67-3.00 Narc**: 95.7%, 52.7, 4.8 Mortality: 0.99%, CI 0.90-1.1	F/U length: 30 d	F/U length: 30 d	F/U length: 30 d	Open group highest rate of complications, then robot, then lap (p<0.01) Highest mortality in open group vs lap (p<0.05) Lowest post-op infection rate in lap vs open and robot (p<0.05) Longer LOS for open patients (p<0.05), no difference lap vs robot No difference in opiate Rx, however higher units used and longer duration in open group	Cost *"postoperative infection" interpreted as SSI **narcotic use assessed by % patients prescribed opiates, mean resource units used/case (units), and mean days of resource units used/case (days)
Bittner, 2018[86]	N=26		N=76	OR time: 365 (78)		OR time: 287 (121)	Readmit: 7.7%		Readmit: 6.6%	F/U length: 90 days		F/U length: 90 days	r-TAR decreased mean hospital LOS by 3 days (p<0.01)	*Post-op complications up to 90 days post-op

Robot vs open TAR + VHR Retrospective cohort (prospective data) Y N 1/1 N N=102	Age: 52.4 (12.9) Male: 33.3% BMI: 33.4 (9) ASA: 3 DM: 0% Tob: 0% Elective: 100% Size (area): 235 (107) [length: 18.5 (5.1), width: 12.3 (3)] Midline: 83% Recurrent: 58.3%		Age: 54.6 (14) Male: 46% BMI: 32.1 (7) ASA: 3 DM: 22.3% Tob: 13% Elective: 100% Size (area): 260 (209) [length: 17.1 (7.1), width: 13.7 (5.9)] Midline: 89.5% Recurrent: 52.6%	Complication: 0% Conversion: 0% Mesh: 100% Closure: 100% Concurrent: 0%		Complication: 5.3% Mesh: 100% Closure: 100% Concurrent: 16%	LOS: 3.8 (1.5) Complication: 19.2%* SSI: 0% Seroma/ hematoma: 1 (3.8%) Mortality: 0% Retention: 2 (7.69%) Other: 1 (3.85%) Ileus: 1 (3.85%)		LOS: 7.1 (5.4) Complication: 30.2%* SSI: 2 (2.6%) Seroma/ hematoma: 0 Mortality: 0% Retention: 6 (7.89%) Other: 25 (32.89%) Ileus: 1 (1.32%)				Longer OR times in r-TAR group (p<0.01) Similar complication rates (p=0.09)	
Carbonell, 2018[90] Robot vs open VHR (TAR permitted) Prospective cohort (AHSQC) Y N 219/181 (14 robot, 39 open after matching) Y N=1205 (333 matched)	N=111 Age: 55.59 (12.36) Race: 86% white Male: 39% BMI: 33.88 (7.30) ASA: 2.60 DM: 25% Tob: 22% Elective: 100% Size: 87.96		N=222 Age: 55.08 (13.76) Race: 82% white Male: 43% BMI: 33.23 (7.39) ASA: 2.62 DM: 25% Tob: 20% Elective: 100% Size: 80.13 cm^2	OR time >2h: 45.05% Complication: 2 (1.80%) Conversion: 3.60% to open Mesh: 100% Closure: 100% Concurrent: 0% TAR: 85%		OR time >2h: 12.61% Complication: 3 (1.35%) Mesh: 100% Closure: 99% Concurrent: 0% TAR: 83%	Readmit: 6% Reop: 2% LOS: 2 (IQR 2) Complication: 66 (29.71%) SSI: 2% SSO: 32% Seroma/ hematoma: 31 (27.93%) Enterotomy: 2 (1.80%) [+1 (0.90%) gastric injury] Pain: 1 (0.90%,		Readmit: 5% Reop: 3% LOS: 3 (IQR 3) Complication: 48 (43.24%) SSI: 4% SSO: 14% Seroma/ hematoma: 11 (4.95%) Enterotomy: 3 (1.35%) Pain: 1 (0.45%, readmission) Mortality: 2 (0.90%)	F/U length: 30 d		F/U length: 30 d	Shorter OR times with open repair (p<0.001) Decreased LOS with robot VHR (p<0.001) No difference in intraop complications (p=1), reoperations, readmissions, or SSIs, but higher proportion of robot patients experienced SSOs (p<0.001), mostly seromas (p<0.001)	First author and several others received honoraria or grants from Intuitive Robotic data overlaps with Warren, 2016

	cm^2 (67.57) , width 7.51 (3.34), length 13.17 (6.58) Recurr ent: 38%		(74.02), width 7.17 (3.68), length 12.00 (6.89) Recurre nt: 37%				readmissio n) Mortality: 0							
Chen, 2016[100] Robot vs lap VHR Retrospectiv e cohort Y N 1/3 N N=72	N=39 Age: 47.2 {24-69} Male: 43.6% BMI: 33 {23- 53} ASA: 2.15 DM: 12.82 % Size: 3.07 cm {1- 9} Recurr ent: 10.26 %	N=33 Age: 46.6 {27-68} Male: 72.7% BMI: 32 {25-45} ASA: 1.97 DM: 15.15% Size: 2.02 cm {0.5-5} Recurre nt: 9.09%		OR time: 156.6 {77-261} Mesh: 100% Closure: 7.69%	OR time: 65.9 {25- 128} Mesh: 100% Closure: 0		LOS: 0.49 {0-3} (for N=14) Complicati on: 3 (7.7%) SSI: 0 Seroma/ hematoma : 1 (2.56%) Retention: 2 (5.13%)	LOS: 0.21 {0-1} (for N=7) Complicati on: 3 (9.1%) SSI: 1 (3.03%) Seroma/ hematoma : 1 (3.03%) Retention: 1 (3.03%)		F/U length: 47 d Recur*: 0	F/U length: 47 d Recur*: 0		Longer operative time in robot group (p<0.0001) Larger hernia sizes in robot group (p<0.0001) No difference in LOS for those who stayed (p=0.09) No difference in complications (p=1)	{}=range *30-d recurrence
Coakley, 2017[98] Robot vs lap VHR Prospective cohort (HCUP-NIS) Y N NR/NR N N=32594	N=351 Age: 59.4 (14.6) Race: 73% white, 11.3 AA, 9.5% Hispan ic, 6.2% other Male: 48% BMI>3 0: 20.5%	N=3224 3 Age: 57.4 (14.9) Race: 75.3% white, 10.5% AA, 10.1% Hispani c, 4.1% other Male: 43% BMI>30 : 25.3% ASA: NR [CCI		Concurre nt: 0%	Concurre nt: 0%		LOS: 3.5 (3.6) Complicati on: 20.24% SSI: 0.85% SSO: 0.28% Mortality: 0% Other: 13.7% Ileus: 5.41%	LOS: 3.4 (2.6) Complicati on: 18.73% SSI: 0.47% SSO: 0.07% Mortality: 0.1% Other: 9.75% Ileus: 8.34%					No difference between LOS (p=0.2), minor or major complication rates (p=0.858, p=0.226), mortality (p=0.478)	Cost/utilization CCI = Charlson comorbidity index

	ASA: NR [CCI 1.1 (1.7)] DM: 18.0% Elective: 100%	0.83 (1.3)] DM: 22.2% Elective: 100%												
Gonzalez, 2015[95] Robot vs lap VHR Retrospective cohort Y N 1/2 N N=134	N=67 Age: 56.6 (14.5) Male: 38.8% BMI: 34.7 (9.0) ASA: 2.2 (0.7) Midline: 65.6%	N=67 Age: 55.0 (13.2) Male: 31.4% BMI: 33.5 (9.5) ASA: 2.0 (0.8) Midline: 74.6%		Skin-skin time: 107.6 (33.9) Conversion: 1 (1.5%) to open Mesh: 100% Closure: 100% Concurrent: 3.0%	Skin-skin time: 87.9 (53.1) Conversion: 3 (4.5%) to open Mesh: 100% Closure: 0% Concurrent: 4.5%		Reop: 1 (1.5%)* LOS: 2.5 (4.1) Complication: 2 (3.0%) SSO: NR Seroma/ hematoma: NR Enterotomy: NR Mortality: 0% Other: 1 (1.5%)	Reop: 2 (3.0%) LOS: 3.7 (6.6) Complication: 7 (10.4%) SSI: 2 (3.0%) Seroma/ hematoma: 2 (3.0%) Enterotomy: 1 (1.5%) Mortality: 0% Other: 2 (3.0%)		1-yr F/U: NR F/U length: 17.1 mo (9.5) Mesh infxn: 1 (1.5%) Recur: 1 (1.5%)	1-yr F/U: NR F/U length: 21.7 mo (12.1) Mesh infxn: NR Recur: 5 (7.5%)		Longer surgical time for PCD (robot) by 19.7 (p=0.012) Longer follow-up for NPCD (lap) by 4.6 mo (p=0.016) Trend toward increased complications (p=0.084) and recurrences (p=0.095) in NPCD (lap) No difference in LOS (p=0.461) or rate of conversion (p=0.310)	*SBO requiring reoperation 4 mo post-op PCD vs non-PCD associated with robot vs lap
Guzman-Pruneda, 2020 (#1457) Robot vs open VHR + CS Prospective database (AHSQC) Y N NR/303 N N=236	N=42 Age: 59 {54-65} Male: 36% BMI: 32 {28-39} ASA: 2.60 DM: 19% Tob: 14% Elective: 100% Area: 61 {40-120}; length		N=194 Age: 62 {53-68} Male: 57% BMI: 31 {28-35} ASA: 2.73 DM: 22% Tob: 3% Elective: 100% Area: 193 {106-300}; length 19 {15-25};	OR time >240: 33% Comp: 0% Conversion to open: 7.1% Mesh: 100%		OR time >240: 18% Comp: 0% Mesh: 100%	Readmit: 1 (2%) Reop: 1 (2%) LOS: 1.5 {1-2.8} Comp: 4 (9.5%) SSI: 0 (0%) SSO: 3 (7.1%) Seroma: 2 (4.8%) Hematoma: 1 (2.4%) Other: 1 (2.4%) QOL: 50 {35-59}		Readmit: 13 (7%) Reop: 3 (2%) LOS: 5 {4-6} Comp: 30 (15.5%) SSI: 3 (1.5%) SSO: 17 (8.8%) Seroma: 5 (2.6%) Hematoma: 2 (1.5%) Other: 10 (5.2%) QOL: 46 {28-72}	1-yr F/U: 100% Recur: 10 (24%) QOL: 90 {58-94}		1-yr F/U: 100% Recur: 38 (20%) QOL: 88 {67-93}	Significantly shorter LOS with robot (p<0.01) Otherwise no significant differences between robot and open approaches for QOL (p=0.66), wound morbidity (p=0.53), readmission (p=0.36), or recurrence (p=0.28)	{}=IQR *Only patients with 1 or fewer hernia recurrences included QOL described by HerQLes score

	13 {8-19}; width 7 {5.2-8.8} Recur*: 33% QOL: 38 {20-67}		width 13 {9-16} Recur*: 31% QOL: 43 {20-67}											
Khorgami, 2018[94] Robot vs lap VHR Prospective cohort (HCUP-NIS, AHRQ) Y N NR/NR N N=3699	N=99	N=3600		Concurrent: 0%	Concurrent: 0%		LOS: 2.9 (3.1)	LOS: 2.7 (1.9)						Cost Data pooled into robot vs lap for multiple procedures (chole, VHR, colectomies, sigmoidectomy, APR, TAH) – no subgroup analyses for outcomes
Lu, 2019 (#1479) Robot vs lap VHR Retrospective cohort Y N 1/NR N N=206	N=86 Age: 50.8 (12.8) Male: 47.6% BMI: 34.4 (7.4) ASA: 2.4 (0.52) DM: 19.8% Size: 7.1 (2.6) Recur: 18.6%	N=120 Age: 53.2 (14.6) Male: 61.7% BMI: 31.3 (6.1) ASA: 2.1 (0.52) DM: 8.3% Size: 5.5 (1.8) Recur: 18.3%		OR time: 174.7 (44.9) Mesh: 100%	OR time: 120.4 (35.0) Mesh: 100%		Readmit: 2 (2.3%) Reop: 2 (2.3%) LOS: 0.1 (0.5) Comp: 2 (2.3%) SSO: 2 (2.3%) Seroma: 0 (0%) Hematoma: 1 (1.2%) Other: 0 (0%)	Readmit: 3 (2.5%) Reop: 3 (2.5%) LOS: 0.2 (0.9) Comp: 11 (9.2%) SSO: 6 (6.7%) Seroma: 4 (3.3%) Hematoma: 2 (1.7%) Other: 3 (2.5%)		1-yr F/U: 73.8% F/U: 5.5 mo (5.9) Recur: 1 (1.2%)	1-yr F/U: 33.3% F/U: 5.7 mo (4.9) Recur: 2 (1.7%)		Longer OR times in robot group (p<0.001) Higher rate of complications with lap (p=0.046) No significant differences for LOS (p=0.294), reoperation (p=0.938), readmission (p=0.938), and recurrence (p=0.771) In a subgroup analysis of patients (n=71) with at least 12-mo follow-up, there was no difference in complications or recurrence	QOL described by Carolina Comfort Scale (CCS)

Martin-del-Campo, 2018[87] Robot vs open TAR + VHR Retrospective cohort Y N 2/NR Y (defect size) N=114	N=38 Age: 58.9 (12.7) Male: 39.5% BMI: 33.1 (8.8) ASA□3: 50% DM: 18.4% Tob: 15.8% Elective: 100% Size (width): 13.5 (4.5) Recurrent: 28.9%		N=76 Age: 58.8 (11.8) Male: 32.9% BMI: 33.51 (5.7) ASA□3: 75% DM: 22.3% Tob: 9.2% Elective: 100% Size (width): 13.5 (4.5) Recurrent: 64.5%	OR time: 299 (95) EBL: 49 (60) Transfxn: 0% Complication: 0% Conversion: NR Mesh: 100%		OR time: 211 (63) EBL: 139 (149) Transfxn: 6.57%* Complication: 0% Mesh: 100%	Readmit: 0% LOS: 1.3 (1.3) Complication: 0% SSO: 1 (2.6%) Mortality: 0% Other: 0% Ileus: 0%		Readmit: 2 (2.64%) LOS: 6 (3.4) Complication: 13 (17.1%) SSO: 9 (11.8%) Mortality: 0% Other: 10 (13.15%) Ileus: 3 (3.95%)				Longer OR times for r-TAR (p<0.001) Lower EBL for r-TAR (p<0.001) No difference between in-hospital transfusions (p=0.106) Higher rate of systemic complications with o-TAR (p=0.007) No difference in wound morbidity (p=0.101) Shorter hospital stay in r-TAR (p<0.001)	*Post-op transfusion
Mudyanadzo, 2020 (#1503) Robot vs lap VHR Retrospective cohort Y N 1/NR N N=35	N=16 Elective: 100% Recur: 0%	N=19 Elective: 100% Recur: 0%					LOS: 1.3 (0.1) Pain*: 1 (6.2%) Narc**: 4.2 (4.25)	LOS: 1.7 (0.2) Pain*: 6 (31.6%) Narc**: 14.5 (5.218)		F/U: 8 w	F/U: 8 w		Similar LOS between groups (p n.s.) Decreased pain in robot group (p<0.05) Increased narcotic use in lap group (p<0.05)	*Pain measured as requiring additional narcotics within follow-up period **Narcotic use defined as daily opioid use (morphine equivalents)
Nguyen, 2017[88] Robot vs open TAR + VHR Retrospective cohort Y N 1/1 N	N=27 Age: 55.4 (12.4) BMI: 32.2 (6.4) Size (area): 216		N=16 Age: 58.6 (10.4) BMI: 33.3 (5.5) Size (area): 242	OR time: 272.1 EBL: 43 Mesh: 100%		OR time: 206.5 EBL: 146.9 Mesh: NR	Readmit: 0% Reop: 0% ED: 4 (14.81%) LOS: 3.0 SSO: 1 (3.70%) Seroma/ hematoma: NR Other: NR		Readmit: 2 (12.5%) Reop: 2 (12.5%) ED: 4 (25%) LOS: 9.6 SSO: 3 (18.75%) Seroma/ hematoma: 1 (6.25%) Other: 4 (25%)				Decreased LOS (p<0.001) and EBL (p<0.001) for RAR Longer OR times for RAR (p<0.001) OAR patients more likely to be admitted (p=0.132) and undergo reoperation	

N=43 Abstract only														
Prabhu, 2017[96] Robot vs lap VHR Prospective cohort (AHSQC) Y N 181/100 (40 robot, 79 lap) Y N=1103 (638 matched for fascial closure)	N=200 (186 matched) Age: 59 {48-68} Race: 85% white Male: 41% BMI: 32 {28-36} ASA (2): 47% DM: 19% Tob: 17% Elective: 100% Size: 19 cm^2 {7-47} (width 4 cm {3-6}, length 6 cm {3-11}) Recurrent: 33%	N=903 (452 matched) Age: 59 {48-68} Race: 84% white Male: 41% BMI: 32 {28-37} ASA (2): 47% DM: 19% Tob: 15% Elective: 100% Size: 16 cm^2 {7-38} (width 4 cm {3-6}, length 5 cm {3-8}) Recurrent: 31%		OR time >2h: 46% Transfxn: 1 (0.54%) Complication: 4 (2.15%) Mesh: 100% Closure: 91%	OR time >2h: 30% Transfxn: 0 Complication: 4 (0.88%) Mesh: 100% Closure: 90%		Readmit: 5 (2.69%) Reop: 0 LOS: 0 (IQR 2.00) Complication: 14 (8%) SSI: 1% SSO: 5% Seroma/ hematoma: 4% Enterotomy: 0 Pain: 1 (0.54%) Mortality: 1 (0.54%) Other: 2 (1.08%) Ileus: 1 (0.54%)	Readmit: 19 (4.20%) Reop: 8 (1.77%) LOS: 1 (IQR 2.00) Complication: 84 (19%) SSI: 1% SSO: 12% Seroma/ hematoma: 10% Enterotomy: 4 (0.88%) Pain: 2 (0.44%) Mortality: 0 Other: 19 (4.20%) Ileus: 8 (1.77%)		F/U length: 30 d	F/U length:30 d		Higher rate of fascial closure in robot group (93% vs 56%, p<0.05) Post-hoc analysis (N=638, matched for fascial closure), hernia length was longer (p=0.01) and OR time was longer (p<0.001) in robot group; increased SSO (p=0.006) or any complication (p<0.001) in lap group Increased LOS in lap group (p<0.001) without difference in readmission (p=0.4) or reoperation (p=0.1128)	First author received grant money from Intuitive {}=range
Roberts, 2019 (#1585) Robot vs open VHR + TAR Prospective database (AHSQC) Y N 1/NR	N=13 Area: 87.4		N=12 Area: 175.9	OR time: 297.9 Conversion to open: 7.7%		OR time: 267.8	LOS: 1.67 Seroma: 1 (7.7%) Hematoma: 1 (7.7%) Pain*: 0 (0%)		LOS: 6.5 Seroma: 10 (8.3%) Hematoma: 10 (8.3%) Pain*: 3 (25%)				No difference in OR time (p=0.47) or hematoma/seroma (p=0.95) Decreased LOS for robot (p<0.0001) Trend toward decreased readmission for pain in robot group (p=0.0546)	*Pain defined as 30-day readmission due to pain

N N=25 Abstract only														
Song, 2017[103] Robot vs lap vs open VHR Retrospective cohort Y N NR/NR (Premier Perspective Database) Y N=6642 (N=286 matched) Abstract only	N=96 matched vs open (N=94 matched vs lap) Elective: 100%	N=1992 (N=94 matched) Elective: 100%	N=4354 (N=96 matched) Elective: 100%	OR time: 231 (101) Transfxn: 0% Complication: 1 (1.0%) Conversion: 2 (2.1%)	OR time: 169 (108) Transfxn: 5 (5.3%) Complication: 4 (4.3%) Conversion: 13 (13.9%)	OR time: 163 (101) Transfxn: 5 (5.2%) Complication: 1 (1.0%)	LOS: 3.0 (2.4) Complication: 17 (17.7%) SSO: 0% Seroma/ hematoma: 0% Narc*: 48 (30, 96)	LOS: 3.2 (3.0) Complication: 23 (24.5%) SSO: 0% Seroma/ hematoma: 3 (3.2%) Narc*: 60 (30, 60)	LOS: 5.3 (5.2) Complication: 38 (39.6%) SSO: 3 (3.1%) Seroma/ hematoma: 4 (4.2%) Narc*: 93 (48, 159)	Mesh infxn: 0%	Mesh infxn: 0%	Mesh infxn: 0%	Lower complications RVHR compared to OVHR (p=0.001), Fewer blood transfusions in RVHR compared to LVHR and OVHR (p=0.02) Fewer conver. compared to LVHR (p=0.003) Less in-hospital PCA compared to OVHR (p=0.02) Shorter LOS compared to OVHR (p=0.003) Longer OR time compared to LVHR and OVHR (p<0.0001)	Obese patients only (BMI>30) Cost analysis *In-hospital PCA morphine equivalent dosage (Q1, Q3)
Switzer, 2017[89] Robot vs open VHR Prospective cohort (AHSQC) Y N NR/NR Y N=120 Abstract only	N=30 Age: 58 (IQR 51-63) Male: 27% Size (width): 7 cm		N=90 Age: 61 (IQR 52-68) Male: 31% Size (width): 6 cm				Readmit: 3% Complications: NR HerQLes: 48		Readmit: 3% Complications: NR HerQLes: 48	F/U: 1 yr Recur: 23% QOL (HerQLes): 82		F/U: 1 yr Recur: 19% QOL (HerQLes): 81	Similar complication rates (p=0.29) No significant difference in 1-year recurrence (p=0.6) Improved QOL outcomes in both robotic and open repairs without major differences at 30 days (p=0.54) or 1 year (p=0.86)	
Walker, 2018[97] Robot vs lap VHR Retrospective cohort Y N	N=142 Age: 53.2 (13.2) Male: 50.0% BMI: 31.6 (5.1)	N=73 Age: 49.5 (13.3) Male: 32.8% BMI: 35.7 (7.9)		Skin-skin time: 116.9 (47.9) Conversion: Mesh: 100%	Skin-skin time: 98.7 (56.6) Conversion: Mesh: 100%		LOS: 1.4 (0.4) SSI: 0 SSO: 24 (16.9%) Seroma/ hematoma: 13 (9.1%)	LOS: 0.7 (0.3) SSI: 5 (6.8%) SSO: 24 (32.8%) Seroma/		F/U length: 12.3 w (2.6) Recur: 11 (7.7%)	F/U length: 23.6 w (8.4) Recur: 5 (6.8%)		Fascial closure more often with robot (p=0.05) Shorter OR times with lap (p=0.03) No difference in recurrence (p=1) Robot had decreased SSO	

2/10 Y (see row below) N=215	ASA: 2.5 (0.7) DM: 13.3% Tob: 31.0% Elective: 100% Size: horizontal 4.3 cm (3.2) Recurrent: 35.2%	ASA: 2.6 (0.7) DM: 19.2% Tob: 38.4% Elective: 100% Size: horizontal 4.1 cm (2.1) Recurrent: 34.2%		Closure: 71.1% Concurrent: 0%	Closure: 54.8% Concurrent: 0%			hematoma: 14 (19.2%)					(p=0.01), seromas (p=0.02), and SSI (p<0.01) Robot had decreased SO on multivariable analysis (OR 0.23, CI 0.08-0.67)	
Walker, 2018[97] Propensity score matched N=96	N=48	N=48		Closure: 77%	Closure: 67%		SSO: 4.2%	SSO: 18.8%		F/U: 4.9 w (IQR 2.0-11.5) Recur: 2.1%	F/U: 6.0 w (IQR 3.9-9.4) Recur: 4.2%		Propensity score matched analysis: robot had increased rates of fascial closure (p<0.01), decreased SSO (p<0.001), decreased recurrence (p<0.01)	
Warren, 2016[101] Robot vs lap VHR (TAR permitted) Prospective cohort (AHSQC) Y N 1/NR N N=156	N=53 Age: 52.9 (12.3) Race: 84.91% white, 7.55% black, 7.55% other Male: 41.51% BMI: 34.7 (7.4) ASA: 2.64 DM: 28.3% Tob: 24.53%	N=103 Age: 60.2 (13.4) Race: 85.44% white, 11.65% black, 2.91% other Male: 26.21% BMI: 35.7 (9.5) ASA: 2.61 DM: 33.01% Tob: 16.5% Size: 88.0 cm^2 (94.0),		OR time: 245.6 (98.5) Complication: 1 (1.89%) Conversion: 0 Mesh: Closure: 96.23% Concurrent: TAR: 43.4%	OR time: 121.5 (57.2) Complication: 9 (8.74%) Conversion: 3.88% to open Mesh: 97.09% Closure: 50.49% Concurrent: TAR: 0%		Readmit: 4 (7.5%) Reop: 2 (3.77%) LOS: 1 {1-3} Complication: 6 (11.32%) SSI: 2 (3.77%) SSO: 28 (52.83%) Seroma/hematoma: 25 (47.17%) Enterotomy: 1 (1.89%) Narc (mg/hr): POD0: 1.9 {1.0-3.7}; POD1: 1.4 {0.4-2.1}	Readmit: 5 (4.8%) Reop: 2 (1.94%) LOS: 2 {2-4} Complication: 7 (6.80%) SSI: 1 (0.97%) SSO: 19 (18.45%) Seroma/hematoma: 17 (16.5%) Enterotomy: 9 (8.74%) Narc (mg/hr): POD0: 2.1 {1.2-3.1}; POD1: 1.8 {0.7-2.7}		F/U length: "short term"	F/U length: "short term"		Fascial defect more likely to be closed with robot (p<0.001) Longer operative time longer for robot (p<0.001) Shorter LOS with robot by 1 day (p=0.004) No difference in narcotic requirement through POD1 (p=0.176) No difference in SSI (p=0.592), but increased SSO with robot (p<0.001), particularly seromas Similar periop complications	Cost {}=IQR

	Size: 82.5 cm^2 (69.8), width 6.5 (2.9) Recurrent: 7.55%	width 6.9 (4.1) Recurrent: 1.94%					Mortality: 0 Other: 3 (5.66%) Ileus: 2 (3.77%)	Mortality: 1 (0.97%) Other: 5 (4.85%) Ileus: 1 (0.97%)					Increased bowel injuries in lap group (p=0.011)	
Zayan, 2019[76] Robot vs lap VHR Retrospective cohort Y N 1/3 N N=49	N=16 Age: 49.0 (IQR 42.2-55.2) Male: 62.5% BMI: 48.97 (IQR 42.15-55.23) ASA: NR DM: 6.25% Tob: 25.0% Elective: 100% Recurrent: 12.5% CCS: 8.8 (IQR -2.5-15.7)	N=33 Age: 51.5 (IQR 46.5-56.2) Male: 42.4% BMI: 33.71 (IQR 30.84-42.88) ASA: NR DM: 15.2% Tob: 9.1% Elective: 100% Recurrent: 12.1% CCS: 23.9 (IQR 12.1-34.1)		OR time: 139 (IQR 108-186) Mesh: 100% Closure: 100% Concurrent: 6.06% BIHR	OR time: 86 (IQR 67-104) Mesh: 100% Closure: 87.9% Concurrent: 0%		LOS (hrs): 22.1 (IQR 9.4-33.7) CCS: 19.0 (IQR -8.3-34.2)	LOS (hrs): 46.3 (IQR 26.3-65.6) CCS: 24.3 (IQR 3.8-33.7)		F/U length: 14.4 mo (IQR 12.9-15.8) Recur: 0% QOL (CCS): 17.2 (IQR 1.7-31.5)	F/U length: 15.1 mo (IQR 13.9-16.2) Recur: 1 (3.0%) QOL (CCS): 6.8 (IQR 2.1-11.4)		No difference in rate of fascial closure (p=0.289) Shorter LOS in robotic VHR (p=0.044) Shorter OR time for lap (p=0.009), although robot operative times decrease with number of cases and are comparable to lap No significant difference in QOL (CCS) outcomes between robot vs lap	Cost

APPENDIX H. CITATIONS FOR EXCLUDED PUBLICATIONS

Cholecystectomy

Comparison (n=4)

1. Ayloo, S., Y. Roh and N. Choudhury (2014). "Laparoscopic versus robot-assisted cholecystectomy: a retrospective cohort study." Int J Surg **12**(10): 1077-1081.
2. Jeong, S. Y., J. W. Lee, S. H. Choi and S. W. Kwon (2018). "Single-incision laparoscopic cholecystectomy using instrumental alignment in robotic single-site cholecystectomy." Ann Surg Treat Res **94**(6): 291-297.
3. Lim, C., G. Bou Nassif, E. Lahat, M. Hayek, M. Osseis, C. Gomez-Gavara, T. Moussalem, D. Azoulay and C. Salloum (2017). "Single-incision robotic cholecystectomy is associated with a high rate of trocar-site infection." Int J Med Robot **13**(4).
4. Morel, P., F. Pugin, P. Bucher, N. C. Buchs and M. E. Hagen (2012). "Robotic single-incision laparoscopic cholecystectomy." J Robot Surg **6**(3): 273-274.

No Outcome of Interest (n=4)

1. Aslam U, Amadi C, Goparaju A, Brathwaite CE, Adrales GL. Trends in Use of Robotic-Assisted Surgery for Inpatient Elective General Surgery in the United States, 2010–2015. *Journal of the American College of Surgeons.* 2019;229(4):S116.
2. Aslam U, Howell RS, Brathwaite CEM, Adrales G. Analysis of Outcomes for Elective Inpatient Robotic-Assisted, Laparoscopic, and Open General Surgery in the United States, 2010–2015. *Journal of the American College of Surgeons.* 2019;229(4):S88.
3. Norwick, P. M., S. Shaheen, J. Blebea, N. Conti, R. Heckburn, M. Zayout, J. Clements and M. Ghanem (2019). "Robotic vs standard laparoscopic cholecystectomy: Clinical outcomes." Surgical Endoscopy **33**: S397.
4. Sheetz KH, Claflin J, Dimick JB. Trends in the Adoption of Robotic Surgery for Common Surgical Procedures. *JAMA Network Open.* 2020;3(1).

No Clinical Data (n=3)

1. Armijo, P. R., S. Pagkratis, E. Boilesen, T. Tanner and D. Oleynikov (2018). "Growth in robotic-assisted procedures is from conversion of laparoscopic procedures and not from open surgeons' conversion: a study of trends and costs." Surg Endosc **32**(4): 2106-2113.
2. Coca-Soliz, VS, R. C. Gooding, J. Hubbard and P. R. Corvo (2017). "Comparison of laparoscope versus da vinci robot on surgical site infections based on operation time and operator volume." Surgical Endoscopy and Other Interventional Techniques **31**: S314.
3. Hirides, S. (2017). "Cholecystectomy using conventional lap, minilap needlescopic or robotic single-site approaches. A technical comparison." Surgical Endoscopy and Other Interventional Techniques **31**(2): S235.

Other (n=2)

1. Aziz, H., M. Zeeshan, R. R. Selby and M. R. Sheikh (2019). "Looking beyond laparoscopic cholecystectomy – Will robotic cholecystectomy be the new the gold standard in patients with advanced liver disease?" HPB **21**: S31.
2. Lee, M. M., K. K. Seeras and J. J. Lim (2019). "Cost comparison of single site robotic and conventional laparoscopic cholecystectomy at a single institution." Surgical Endoscopy **33**: S395.

Review/Editorial (n=8)

1. Awad, M. M. and J. W. Fleshman (2010). "Robot-assisted surgery and health care costs [10]." New England Journal of Medicine **363**(22): 2174-2175.
2. Barbash, G. I. and S. A. Glied (2010). "New technology and health care costs - The case of robot-assisted surgery." New England Journal of Medicine **363**(8): 701-704.
3. Biglarian, S. and N. Katkhouda (2017). "Requesting Patient Characteristics for Readmissions Noted in "Single-site Robotic Cholecystectomy in a Broadly Inclusive Patient Population: A Prospective Study"." Ann Surg **265**(4): e34-e35.
4. Brody, F. and N. G. Richards (2014). "Review of robotic versus conventional laparoscopic surgery." Surgical Endoscopy **28**(5): 1413-1424.
5. Castellanos, A., J. Fazendin and L. Panait (2015). "Single-incision laparoscopic cholecystectomy." Clinical Liver Disease **5**(1): 5-7.
6. Giulianotti, P. C. (2017). "Why I think the robot will be the future for laparoscopic cholecystectomies." Surgery **161**(3): 637-638.
7. Lee, E. K., E. Park, W. O. Oh and N. M. Shin (2017). "CORRIGENDUM: Correction of the affiliation name. Comparison of the outcomes of robotic cholecystectomy and laparoscopic cholecystectomy." Ann Surg Treat Res **93**(4): 229.
8. Newman, R. M., A. Umer and S. Ellner (2016). "Traditional Four-Port vs Single-Incision and Robotically Assisted Cholecystectomy: In reply to Bloomstone and colleagues." J Am Coll Surg **223**(1): 208.

Duplicate (n=11)

1. Armijo, P. R., S. Pagkratis, E. Boilesen, T. N. Tanner and D. Oleynikov (2017). "Growth in robotic-assisted procedures is from conversion of laparoscopic procedures and not from open surgeons conversion: a study of trends and costs." Surgical endoscopy and other interventional techniques. Conference: 2017 scientific session of the society of american gastrointestinal and endoscopic surgeons, SAGES 2017. United States **31**: S31.
2. Balachandran, B., T. Mustafa, T. A. Hufford, K. Kochar, L. M. Prasad, S. Sulo and J. Khorsand (2016). "A comparative study of outcomes between single-site robotic and multi-port laparoscopic cholecystectomy: An experience from a tertiary care center." Surgical Endoscopy and Other Interventional Techniques **30**: S258.
3. Charles EJ, Hunter Mehaffey J, Kane WJ, Hawkins RB, Tache-Leon CA, Yang Z. Robotic compared to laparoscopic cholecystectomy: A propensity matched analysis. *Surgical Endoscopy and Other Interventional Techniques.* 2018;32(1):S34.
4. Gonzalez AM, Verdeja JC, Rabaza JR, et al. Single incision cholecystectomy: Comparative study between laparoscopic, robotic and spider platforms. *Surgical*

Endoscopy and Other Interventional Techniques. 2013;27:S274.
5. Grochola, L. F., C. Soll and S. Breitenstein (2018). "Robot-assisted single-site compared with laparoscopic single-incision cholecystectomy for benign gallbladder disease: results of a single-blinded randomized controlled trial." European surgical research. Europaische chirurgische forschung. Recherches chirurgicales europeennes **59**: 4-.
6. Grochola, L. F., C. Soll, A. Zehnder, R. Wyss, P. Herzog and S. Breitenstein (2018). "Robot-assisted versus laparoscopic single-incision cholecystectomy: results of a randomized controlled trial." Surgical endoscopy.
7. Grochola, L. F., C. Soll, A. Zehnder, R. Wyss, P. Herzog and S. Breitenstein (2018). "Robot-assisted single-site compared with laparoscopic single-incision cholecystectomy for benign gallbladder disease: results of a single-blinded randomized controlled trial." HPB **20**: S726.
8. Grochola, L. F., C. Soll, A. Zehnder, R. Wyss, P. Herzog and S. Breitenstein (2018). "Robot-Assisted Single-Site compared with laparoscopic single-incision cholecystectomy for benign gallbladder disease: Results of a single-blinded randomized controlled trial." Swiss Medical Weekly **148**: 4S.
9. Higgins, R. M., M. J. Frelich, M. E. Bosler and J. C. Gould (2016). "Cost analysis of robotic versus laparoscopic general surgery procedures." Surgical Endoscopy and Other Interventional Techniques **30**: S243.
10. Kaminski, J. P., K. W. Bueltmann and M. Rudnicki (2014). "Robotic versus laparoscopic cholecystectomy: Does the end justify the means?" Surgical Endoscopy and Other Interventional Techniques **28**: 262.
11. Newman, R. M., B. J. Bozzuto, J. L. Dilungo and S. J. Ellner (2014). "The surgical value of nontraditional, minimally invasive gallbladder removal: Traditional 4 port vs single incision and robotically-assisted cholecystectomy." Journal of the American College of Surgeons **219**(4): e34.

Inguinal Hernia Repair

Comparison (n=2)

1. Edelman, D. (2018). "Is robotic inguinal hernia repair safe?" Hernia **22**(1): S103.
2. Edelman, D. S. (2017). "Robotic inguinal hernia repair." Surgical Endoscopy and Other Interventional Techniques **31**: S330.

No Clinical Data (n=3)

1. Delgado, M., J. C. Quispe, K. Medani, C. Wang and E. Yung (2019). "A 5 year retrospective study comparing results of laparoscopic versus robotic inguinal hernia repair." Journal of Investigative Medicine **67**(1): 221.
2. McCoy, K., W. Symons, J. Clarke, M. Novack and M. Broderick (2018). "Open versus robotic inguinal hernia repair: Is there a superior approach?" Surgical Endoscopy and Other Interventional Techniques **32**(1): S346.
3. Verduzco-Gomez, E., A. Badami and F. Sabido (2018). "Robotic inguinal hernia repair eliminates the need for post-operative narcotics and demonstrates lower post-operative pain scores." Hernia **22**(1): S183.

No Outcome of Interest (n=6)

1. Armijo, P. R., S. Pagkratis, E. Boilesen, T. N. Tanner and D. Oleynikov (2017). "Growth in robotic-assisted procedures is from conversion of laparoscopic procedures and not from open surgeons conversion: a study of trends and costs." Surgical endoscopy and other interventional techniques. Conference: 2017 scientific session of the society of american gastrointestinal and endoscopic surgeons, SAGES 2017. United States **31**: S31.
2. Aslam U, Amadi C, Goparaju A, Brathwaite CE, Adrales GL. Trends in Use of Robotic-Assisted Surgery for Inpatient Elective General Surgery in the United States, 2010–2015. *Journal of the American College of Surgeons.* 2019;229(4):S116.
3. Aslam U, Howell RS, Brathwaite CEM, Adrales G. Analysis of Outcomes for Elective Inpatient Robotic-Assisted, Laparoscopic, and Open General Surgery in the United States, 2010–2015. *Journal of the American College of Surgeons.* 2019;229(4):S88.
4. Muysoms, F., C. Ballecer and A. Ramaswamy (2018). "Evaluation of the operative time for robotic assisted laparoscopic groin hernia repair during the learning curve of 125 cases." Surgical Endoscopy and Other Interventional Techniques **32**(1): S144.
5. Sheetz KH, Claflin J, Dimick JB. Trends in the Adoption of Robotic Surgery for Common Surgical Procedures. *JAMA Network Open.* 2020;3(1).
6. Zayadin Y, D'John J, Yaldo B, McKany M. Urinary Retention Post Open vs Laparoscopic vs Robotic Inguinal Hernia Repair: A Comparative Retrospective Review. *Journal of the American College of Surgeons.* 2019;229(4):e129.

Procedure (n=1)

1. Tran, H. (2011). "Robotic single-port hernia surgery." Jsls **15**(3): 309-314.

Systematic Review (n=1)

1. Jacks BE, Agor UJ, Sanni AO. Clinical Outcomes after Robotic Assisted Transabdominal Preperitoneal (R-TAPP) vs Laparoscopic Totally Extraperitoneal (L-TEP) Inguinal Hernia Repair. *Journal of the American College of Surgeons.* 2019;229(4):e109.

Review/Editorial (n=2)

1. Bernhardt, G. A., K. Gruber and G. Gruber (2010). "TAPP repair in a giant bilateral scrotal hernia - limits of a method." ANZ J Surg **80**(12): 947-948.
2. Godshall, E., S. Eckhouse, C. Johnson, A. Patterson and R. Pullatt (2015). "Transabdominal Preperitoneal Inguinal Hernia Repair as a Salvage Operation after Failure of Prior Total Extraperitoneal Repair." Am Surg **81**(8): 312-313.

Duplicate (n=3)

1. Hennings, D. L., P. R. Armijo and D. Oleynikov (2018). "Robotic inguinal hernia repair is superior to open or laparoscopic inguinal hernia repair: A national data base review." Surgical Endoscopy and Other Interventional Techniques **32**(1): S344.
2. Muysoms, F., C. Ballacer, A. Ramaswamy, S. Van Cleven and I. Kyle-Leinhase (2017). "Evaluation of the operative time for robotic assisted laparoscopic groin hernia repair

during the learning curve." Hernia **21**(2): S159.
3. Zayan NE, Meara MP, Schwartz JS, Narula VK. A direct comparison of robotic and laparoscopic hernia repair: patient-reported outcomes and cost analysis. *Hernia.* 2019;23(6):1115-1121.

Unavailable (n=1)

1. Edelman, D. S. (2017). "Robotic Inguinal Hernia Repair." Am Surg **83**(12): 1418-1421.

Ventral Hernia Repair

Comparison (n=6)

1. Halka, J., A. Vasyluk, A. DeMare, A. Iacco and R. Janczyk (2018). "Hybrid robotic assisted transversus abdominis release is associated with a significantly decreased length of stay without increased complications compared to open transversus abdominis release in patients with large ventral hernias." Hernia **22**(1): S27.
2. Halka, J. T., A. Vasyluk, A. Demare, A. Iacco and R. Janczyk (2019). "Hybrid robotic-assisted transversus abdominis release versus open transversus abdominis release: a comparison of short-term outcomes." Hernia **23**(1): 37-42.
3. Muse, T. O., B. A. Zwischenberger, M. T. Miller, D. A. Borman, D. L. Davenport and J. S. Roth (2018). "Outcomes after Ventral Hernia Repair Using the Rives-Stoppa, Endoscopic, and Open Component Separation Techniques." Am Surg **84**(3): 433-437.
4. Oviedo, R. J., J. C. Robertson and A. S. Desai (2017). "Robotic Ventral Hernia Repair and Endoscopic Component Separation: Outcomes." Jsls **21**(3).
5. Sailes, F. C., J. Walls, D. Guelig, M. Mirzabeigi, W. D. Long, A. Crawford, J. H. Moore, Jr., S. E. Copit, G. A. Tuma and J. Fox (2011). "Ventral hernia repairs: 10-year single-institution review at Thomas Jefferson University Hospital." J Am Coll Surg **212**(1): 119-123.
6. Ioannidis A, Machairas N, Koutserimpas C, Spartalis E, Konstantinidis M, Konstantinidis K. Evolution of robot-assisted general surgery in Greece and Cyprus. *Journal of Robotic Surgery.* 2019;13(2):315-317.

No Outcome of Interest (n=7)

1. Addo AJ, Zahiri HR, Broda A, et al. Early Perioperative Outcomes in Obese Patients Undergoing Minimally Invasive Abdominal Wall Reconstruction. *Journal of the American College of Surgeons.* 2019;229(4):e112.
2. Armijo PR, Pagkratis S, Boilesen E, Tanner T, Oleynikov D. Growth in robotic-assisted procedures is from conversion of laparoscopic procedures and not from open surgeons' conversion: a study of trends and costs. *Surgical Endoscopy.* 2018;32(4):2106-2113.
3. Aslam U, Amadi C, Goparaju A, Brathwaite CE, Adrales GL. Trends in Use of Robotic-Assisted Surgery for Inpatient Elective General Surgery in the United States, 2010–2015. *Journal of the American College of Surgeons.* 2019;229(4):S116.
4. Aslam U, Howell RS, Brathwaite CEM, Adrales G. Analysis of Outcomes for Elective Inpatient Robotic-Assisted, Laparoscopic, and Open General Surgery in the United

States, 2010–2015. *Journal of the American College of Surgeons.* 2019;229(4):S88.
5. Forester B, Donovan K, Kuchta K, et al. Short-Term Quality of Life Comparison of Laparoscopic, Open, and Robotic Incisional Hernia Repairs. *Journal of the American College of Surgeons.* 2019;229(4):e127.
6. Sheetz KH, Claflin J, Dimick JB. Trends in the Adoption of Robotic Surgery for Common Surgical Procedures. *JAMA Network Open.* 2020;3(1).
7. Zayan NE, Meara MP, Schwartz JS, Narula VK. A direct comparison of robotic and laparoscopic hernia repair: patient-reported outcomes and cost analysis. *Hernia.* 2019;23(6):1115-1121.

Sample Size (n<10) (n=2)

1. Belyansky, I., A. S. Weltz, U. S. Sibia, J. J. Turcotte, H. Taylor, H. R. Zahiri, T. R. Turner and A. Park (2018). "The trend toward minimally invasive complex abdominal wall reconstruction: is it worth it?" Surgical Endoscopy **32**(4): 1701-1707.
2. Mejia, A., C. G. Fasola and A. Stegall (2019). "Incisional ventral hernia repair (IVHR) in post liver transplant recipients (OLT) through a robotic-assisted intervention (RAI): Initial single-center experience." American Journal of Transplantation **19**: 863-864.

Case series n<10 (n=2)

1. Daes, J. (2014). "Endoscopic subcutaneous approach to component separation." J Am Coll Surg **218**(1): e1-4.
2. Gillespie, J. W., 3rd, D. D. Zabel, M. K. Conway, E. D. Kalish and D. E. Sarmiento Garzon (2015). "Abdominal Wall Reconstruction for Large Ventral Hernias in the Octogenarian." Am Surg **81**(11): E373-375.

Systematic Review (n=1)

1. Souza, J. M. and G. A. Dumanian (2012). "An evidence-based approach to abdominal wall reconstruction." Plast Reconstr Surg **130**(1): 116-124.

Review (n=1)

1. (2012). "Hernia repair: which surgical approach is best?" Johns Hopkins Med Lett Health After 50 **24**(8): 4-5.

Duplicate (n=6)

1. Addo A, Parlacoski S, Ewart Z, Broda A, Zahiri R, Belyansky I. Comparative review of outcomes: Laparoscopic and robotic enhanced-view totally extraperitoneal rives-stoppa abdominal wall reconstruction. *Surgical Endoscopy.* 2019;33:S15.Alrefai, S., M. Mabe, M. Vy, P. Del Prado, N. L. Clingempeel and J. G. Bittner (2017). "Comparative analysis of robot-assisted minimally invasive vs open transvs abdomens release outcomes in abdominal wall reconstruction." Journal of the American College of Surgeons **225**(4): e83-e84.
2. Alrefai S, Mabe M, Vy M, Del Prado P, Clingempeel NL, Bittner JG. Comparative

analysis of robot-assisted minimally invasive vs open transvs abdomens release outcomes in abdominal wall reconstruction. *Journal of the American College of Surgeons.* 2017;225(4):e83-e84.

3. Costa, T. N., R. Z. Abdalla, I. Cecconello and U. Ribeiro (2017). "Randomized clinical trial: Comparison between robotic assisted and laparoscopic incisional hernia repair." Hernia **21**(2): S158.
4. Khorgami, Z., T. Jackson, W. T. Li, C. A. Howard and G. M. Sclabas (2017). "Extra costs of robotic surgery in minor and major surgeries: An analysis of national inpatient sample." Journal of the American College of Surgeons **225**(4): e86.
5. Walker, P., A. May, M. R. Santillan, S. Kim, S. Shah, E. Wilson, M. Liang and S. Tsuda (2017). "Multicenter review of robotic versus laparoscopic ventral hernia repair: is there a role for robotics?" Surgical endoscopy and other interventional techniques. Conference: 2017 scientific session of the society of american gastrointestinal and endoscopic surgeons, SAGES 2017. United states **31**: S29.
6. Weltz, A. S., J. Turcotte, U. S. Sibia, E. Zakharov, N. Wu, T. R. Turner, A. Park, H. R. Zahiri and I. Belyansky (2017). "The trend toward minimally invasive complex abdominal wall reconstruction: Is it worth it?" Surgical Endoscopy and Other Interventional Techniques **31**: S22.

Unavailable (n=1)

1. Espinosa-de-los-Monteros, A. (2012). "[Abdominal wall reconstruction for complex incisional hernias]." Rev Invest Clin **64**(6 Pt 2): 634-640.