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The COMPARE Study: Comparing Perioperative Outcomes of Oncologic Minimally Invasive Laparoscopic, da Vinci Robotic, and Open Procedures

A Systematic Review and Meta-analysis of the Evidence

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Objective: To assess 30-day outcomes of da Vinci robotic-assisted (dV-RAS) versus laparoscopic or video-assisted thoracoscopic (lap/VATS) or open oncologic surgery.

Background: Complex procedures in deep/narrow spaces especially benefit from dV-RAS. Prior procedure-specific comparisons are not generalizable.

Methods: PubMed, Scopus, and EMBASE were systematically searched (latest: November 17, 2023) following Preferred Reporting Items for Systematic Reviews and Meta-Analyses and PROSPERO (Reg#CRD42023466759). Randomized, prospective, and database studies were pooled as odds ratios (ORs) or mean differences (MDs) in R using fixed effects or random effects (heterogeneity significant). ROBINS-I/RoB 2 were used to assess bias.

Results: Of 56,314 unique references over 12 years from 22 countries, 230 studies (34 randomized, 74 prospective, and 122 database) comparing dV-RAS to lap/VATS or open surgery across 7 procedures, 4 specialties, representing 1,194,559 dV-RAS; 1,095,936 lap/VATS and 1,625,320 open cases were included. Operative time for dV-RAS was longer than lap/VATS [MD: 17.73 minutes (9.80, 25.67), $P < 0.01$] and open surgery [MD: 40.92 minutes (28.83, 53.00), $P < 0.01$], whereas hospital stay was shorter [lap/VATS MD: -0.51 days (-0.64, -0.38), $P < 0.01$; open MD: -1.85 days (-2.09, -1.62), $P < 0.01$] and blood loss was less versus open [MD: -293.44 mL (-359.53, -227.35)]. There were fewer dV-RAS conversions [OR: 0.44 (0.40, 0.49), $P < 0.01$], transfusions [OR: 0.79 (0.72, 0.88), $P < 0.01$], postoperative complications [OR: 0.90 (0.84, 0.96), $P < 0.01$], readmissions [OR: 0.91 (0.83, 0.99), $P = 0.04$], and deaths [OR: 0.86 (0.81, 0.92), $P < 0.01$] versus lap/VATS, and fewer transfusions [OR: 0.25 (0.21, 0.30), $P < 0.01$], postoperative complications [OR: 0.56 (0.52, 0.61), $P < 0.01$], readmissions [OR: 0.71 (0.63, 0.81), $P < 0.01$], operations [OR: 0.89 (0.81, 0.97), $P < 0.01$], and deaths [OR: 0.54 (0.47, 0.63), $P < 0.01$] versus open surgery. Blood loss [MD:- 12.26 mL (-29.44, 4.91), $P = 0.16$] and operations [OR: 1.03 (0.95, 1.11), $P = 0.48$] were similar for dV-RAS and lap/VATS. There was significant heterogeneity.

Conclusions: Da Vinci-RAS confers benefits across oncological procedures and study designs. These results provide clinical evidence to multispecialty-care decision-makers considering dV-RAS.

Key Words: cancer surgery, da Vinci, meta-analysis, oncologic surgery, outcomes, perioperative, robot surgery

(*Ann Surg* 2025;281:748–763)

Minimally invasive surgery (MIS) has transformed the surgical management of disease. Compared with open surgery, traditional MIS (endoscopy, laparoscopy, and video-assisted thoracoscopy) offers a number of benefits including smaller incisions, less morbidity, faster recovery, reduced pain, shorter length of hospital stay, and improved cosmesis.[1–5] However, it has several technical limitations, most notably lower quality vision and depth perception from two-dimensional imaging, camera instability from a hand-held design, limited range motion and dexterity from straight and rigid hand-held instruments capable of only 4 degrees of movement, a propensity for surgeon fatigue, work-related musculoskeletal injuries and tremor from physically demanding ergonomics, and a steep learning curve.[6–8] The da Vinci robotic-assisted surgery (dV-RAS) system (Intuitive Surgical Inc.) received U.S. Food and Drug Administration approval in 2000 and advanced MIS by overcoming many of the technical limitations.[6,9] Collectively, da Vinci's technological advancements facilitated the accuracy and precision of MIS dissection and reconstruction, most appreciably within deep, limited, or narrow cavities, such as the chest, abdomen, and pelvis, and enabled the expansion of MIS into more highly complex surgical procedures compared with traditional minimally invasive approaches.[6,10–12]

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This study did not require ethics approval as it deals with previously published data.

U.S.K., A.Y., N.M.P., and A.E.H. are employees of Intuitive Surgical. The remaining authors report no conflicts of interest.

Supplemental Digital Content is available for this article. Direct URL citations are provided in the HTML and PDF versions of this article on the journal's website, www.annalsofsurgery.com.

DOI: 10.1097/SLA.0000000000006572

There is an abundance of research comparing perioperative outcomes between dV-RAS, traditional MIS [laparoscopic or video-assisted thoracoscopic surgery (lap/VATS)], and open surgery for individual surgical procedures.[13–17] These studies generate procedure-specific evaluations of robotic-assisted surgery. Few studies encompass a more comprehensive evaluation of robotic-assisted surgery by comparing perioperative outcomes by surgical approach across multiple surgical procedures.[18–23] Thus far, the meta-analyses[18,19,21–23] comparing perioperative outcomes by surgical approach across procedures have been subject to the following limitations: (1) restricted study design eligibility to randomized controlled trials (RCTs)[18,19,21,22] despite limited numbers of RCTs and the majority of existing RCTs exhibiting small sample sizes (< 30 patients per arm),[18,23] (2) pooled analysis comparisons of perioperative outcomes between robotic-assisted surgery and laparoscopic surgery only (due to inadequate numbers of robotic-assisted vs open surgery publications or limited scope),[18,21,22] (3) a lack of a common set of clinical outcomes across prospective studies, (4) evaluation of an extensive range of surgical procedures and complexities such as, but not limited to, combining benign and oncologic surgical indications,[18,19,22,23] and (5) limited reporting of important perioperative outcomes including conversions, 30-day mortality, 30-day readmissions and 30-day reoperations.

The current systematic review and meta-analysis address these limitations by including RCTs as well as expanding study design eligibility to enable the use of real-world data derived from prospective cohort and large databases studies published within the last 12 years (2010–2022), increasing the number of perioperative outcomes for pooled comparisons between dV-RAS and laparoscopic surgery and dV-RAS versus open surgery, and focusing on studies of complex oncologic surgery commonly performed in the deep, limited and narrow spaces of the thoracic (lobectomy), abdominal [hysterectomy, colectomy, and partial nephrectomy (PN)] and pelvic (prostatectomy, low anterior resection/TME/intersphincteric resection) cavities. The aim of this meta-analysis was to determine whether oncologic surgery performed with the dV-RAS surgical system was associated with improvements in 30-day perioperative outcomes compared with lap/VATS or open surgery.

METHODS

This systematic review and meta-analysis was performed and reported in accordance with the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" guidelines[24] (Supplemental Digital Content Tables 1 and 2, http://links.lww.com/SLA/F333) and is registered in PROSPERO international prospective register of systematic reviews (CRD42023466759). The protocol is available upon request. Separate searches were performed for each procedure in PubMed, Embase, and Scopus (last searched on November 17, 2023) for papers published between January 1, 2010 and December 31, 2022. Search strategies included combinations of robotic keywords: "da Vinci," "robot*," "minimally invasive," and procedure-specific terms: "lobectomy," "hysterectomy," "prostatectomy," "nephrectomy," "colectomy," low anterior resection," "mesorectal," and cancer terms: "carcinoma," "malignancy," "oncologic." The complete search terms used for each database are listed in Supplemental Tables 3 and 4 (Supplemental Digital Content Tables 3 and 4, http://links.lww.com/SLA/F333) for right colectomy and PN, and the remaining procedures were referenced elsewhere.[25] Two researchers screened each reference and checked the papers for relevancy. The full text of relevant studies was evaluated for eligibility based on inclusion and exclusion criteria. Finally, data from the lists of eligible publications were manually extracted. The extracted data were quality control checked by 2 researchers in its entirety.

Inclusion criteria consisted of: (1) a study reporting on at least one primary, nonmetastatic, oncologic surgery performed with the dV-RAS surgical system within the chest, abdominal and pelvic cavities, including lung lobectomy, total or radical hysterectomy, PN, right colectomy, radical prostatectomy, or low anterior resection/TME/intersphincteric resection, (2) a peer-reviewed manuscript published between January 1, 2010 and December 31, 2022 (to include the widespread use of the da Vinci Si and Xi systems, the clearance by the FDA of multiple procedures, and the expansion of robotic use to more than just pioneer surgeons), and (3) a study design inclusive of RCTs, database studies, and prospective studies comparing dV-RAS with laparoscopic/VATS or open surgery.

Exclusion criteria included: (1) a non-English language publication, (2) a pediatric study population, (3) a non–peer-reviewed health technology assessment publication, (4) a study of an alternate surgical technique or approach (eg, transanal surgery, single-portal surgery, and hand-assist surgery), (5) a study with no stratified analysis by study arm (eg, combined results from dV-RAS, lap/VATS, or open cohorts), (6) a study reported only combined data from multiple procedures or indications (ie, the inclusion of procedures and indications beyond the scope of the procedures included in this study), (7) the study did not report any 30-day perioperative clinical outcomes of interest, and (8) the study included a redundant patient population and similar conclusions. The 30-day perioperative outcomes of interest included: conversions to open surgery, operative time (OT), blood transfusions, estimated blood loss, length of hospital stay, 30-day complications, 30-day readmissions, 30-day operations, and 30-day mortality. Data extraction was performed using a standardized data collection form. The first author's name, publication year, study type, sample size, country of origin, database used, and the outcomes of interest were extracted from each study. Data were then standardized to mean and SD (continuous outcomes) and event n and total n for binary outcomes. Studies reporting outcomes of interest in a way that could not be standardized and pooled with the other papers were included in the review, but not in the meta-analysis, with the specific reasons reported in the flowchart. Quality assessment was performed by 2 reviewers (A.Y. and N.M.P.). Disagreements were adjudicated by discussion and consensus between reviewers. Meta-analyses were conducted using R Software[26] forest plots for each outcome and comparisons were created and summarized into main forest plots showing results by procedure. Analyses were performed separately for dV-RAS versus lap/VATS and dV-RAS versus open surgery. The measure of effect for each perioperative outcome pooled across 7 oncologic procedures was analyzed either as an odds ratio (OR) or risk difference (RD) with 95% CI for binary outcomes (conversions, blood transfusions, 30-day complications, 30-day readmissions, 30-day operations, and 30-day mortality) or as a weighted

mean difference (MD) with 95% CI for a continuous outcome (OT, blood loss, and length of hospital stay). An RD was also calculated in instances where an OR could not be calculated for studies in the analysis due to zero event rates in both comparison cohorts. A fixed-effect model was used when heterogeneity was not statistically significant (χ^2, $P \geq 0.05$ or $I^2 < 50\%$) while a random-effect model was used otherwise. Individual studies were weighted in the pooled analysis based on a combination of the study sample size and the variability of the outcome of interest. This weighting was also used to calculate means, SDs, proportions, and 95% CIs. A 2-tailed value of $P < 0.05$ was considered statistically significant. Subgroup analysis was performed by study type. Bias was assessed using the Cochrane Risk of Bias (ROBINS-I and RoB-2) tools by 2 reviewers for randomized and nonrandomized studies and publication bias was assessed using visual analysis of funnel plots. Data collection forms, extracted data, forest plots showing individual studies, and the R code utilized are available upon request.

RESULTS

A total of 56,314 unique references were screened, with 230 publications comparing dV-RAS to lap/VATS and open surgery that meet inclusion criteria and were included in the meta-analysis. These publications included 7 oncologic surgeries within 4 surgical specialties and covered 12 years of peer-reviewed published work from over 22 countries globally. They include 34 RCTs, 74 prospective studies, and 122 database studies representing 1,194,559 dV-RAS, 1,095,936 lap/VATS, and 1,625,320 open cases (Fig. 1 and Supplemental Digital Content Figs 1–6, http://links.lww.com/SLA/F333, bibliography of included studies in Appendix A, Supplemental Digital Content 1, http://links.lww.com/SLA/F333). There were 84 papers that compared dV-RAS to lap/VATS, 71 papers that compared dV-RAS to open surgery, and 75 papers that compared all 3 surgical approaches. The year of publication for the various comparison types is shown in Supplementary Table 5, (Supplemental Digital Content Table 5, http://links.lww.com/SLA/F333), and shows no difference in the distribution of publications by year for the 3 comparison paper types (χ^2, $P = 0.2374$), or for publications with a laparoscopic cohort versus dV-RAS/Open comparison papers (χ^2, $P = 0.052$). The median year of publication was also calculated and was 2019 for comparisons including a lap/VATS cohort, and 2017 for dV-RAS versus open papers. Papers included in the review, but not the meta-analysis are listed at the end of each procedure in Appendix A (Supplemental Digital Content 1, http://links.lww.com/SLA/F333), are listed in the flowcharts (Supplemental Digital Content Figs 1–6, http://links.lww.com/SLA/F333), and Supplemental Table 12 (Supplemental Digital Content Table 12, http://links.lww.com/SLA/F333) reports the data as it was presented in the paper.

Study characteristics by procedure type are provided in Supplemental Tables 6–11 (Supplemental Digital Content Tables 6–11, http://links.lww.com/SLA/F333). These include the type of study (RCT, Database, and Prospective), the time period when data was collected, the sample size of each comparative cohort, the outcomes that were reported and analyzed, and a summary of the Risk of Bias assessments based on either the ROBINS-I or RoB-2 tools depending on the type of study. In general, there was a higher risk of bias among database and prospective studies, especially in the domains of potential confounding and selection. RCTs had a lower overall risk of bias in general, with bias mainly arising from domains pertaining to the randomization process or deviations from intended interventions. The overall results of the meta-analysis pooled across procedures, comparing dV-RAS versus lap/VATS and dV-RAS versus open surgery are provided for the 9 clinical outcomes of interest in Table 1 and Supplemental Figures 7–23 (Supplemental Digital Content Figs. 7–23, http://links.lww.com/SLA/F333). Summary forest plots for each of the outcomes by cohort comparisons are provided in Figures 2–4, with any procedure subgroup-specific RD calculations reported in the footnotes for comparison.

OT was longer by 17.7 minutes for dV-RAS in comparison to lap/VATS and by 40.9 minutes in comparison to open surgery, both results were statistically significant $P < 0.01$ and $P < 0.01$, respectively. dV-RAS cases were 56% less likely to convert to open surgery compared with lap/VATS cases [OR: 0.44 (0.40, 0.49), $P < 0.01$]. There was a statistically significant difference in estimated blood loss between dV-RAS and open cases by 293.44 mL ($P < 0.01$), with no difference seen relative to lap/VATS ($P = 0.16$). There was a significant difference when comparing the likelihood of receiving a blood transfusion: dV-RAS cases were 21% less likely to receive a blood transfusion versus lap/VATS counterparts [OR: 0.79 (0.72, 0.88), $P < 0.01$] and were 75% less likely to be transfused relative to those undergoing open surgery [OR: 0.25 (0.21, 0.30), $P < 0.01$]. dV-RAS cases were 10% less likely to experience a postoperative complication within 30 days versus the lap/VATS cohort [OR: 0.90 (0.84, 0.96), $P < 0.01$] and 44% less likely compared with those undergoing open surgery [OR: 0.56 (0.52, 0.61), $P < 0.01$]. Cases in the dV-RAS group resulted in a half-a-day savings in hospital stay when compared with lap/VATS cases and 1.85 days of hospital stay savings in comparison to open cases, ($P < 0.01$, $P < 0.01$). Readmissions within 30 days of surgery were less likely to occur after dV-RAS when compared with lap/VATS [OR: 0.91 (0.83, 0.99), $P = 0.04$], and open surgery [OR: 0.71 (0.63, 0.81), $P < 0.01$]. Patients undergoing dV-RAS and lap/VATS were just as likely to be reoperated within 30 days of surgery; however, when compared with open cases, dV-RAS resulted in an 11% lower likelihood of reoperation [OR: 0.89 (0.81, 0.97), $P < 0.01$]. Mortality within 30 days of surgery was significantly lower after dV-RAS: relative to lap/VATS [OR: 0.86 (0.81, 0.92), $P < 0.01$] and open surgery [OR: 0.54 (0.47, 0.63), $P < 0.01$]. Funnel plots are provided in Supplemental Figure 24 (Supplemental Digital Content Fig. 24, http://links.lww.com/SLA/F333).

Subgroup Analysis: da Vinci Robotic-assisted Versus Laparoscopic or Video-assisted Thoracoscopic Surgery

A stratified analysis of each clinical outcome by study type was conducted to understand the impact of study design; RCT, Database, or Prospective on each outcome (Tables 2 and 3). When comparing dV-RAS and lap/VATS, OT was significantly longer by an average of 26.8 minutes and 28.9 minutes according to RCT and Database studies; however, no difference was seen among prospective studies. Conversions to open surgery were statistically significant in favor of dV-RAS regardless of study design. There was no difference in blood loss between dV-RAS and lap/VATS

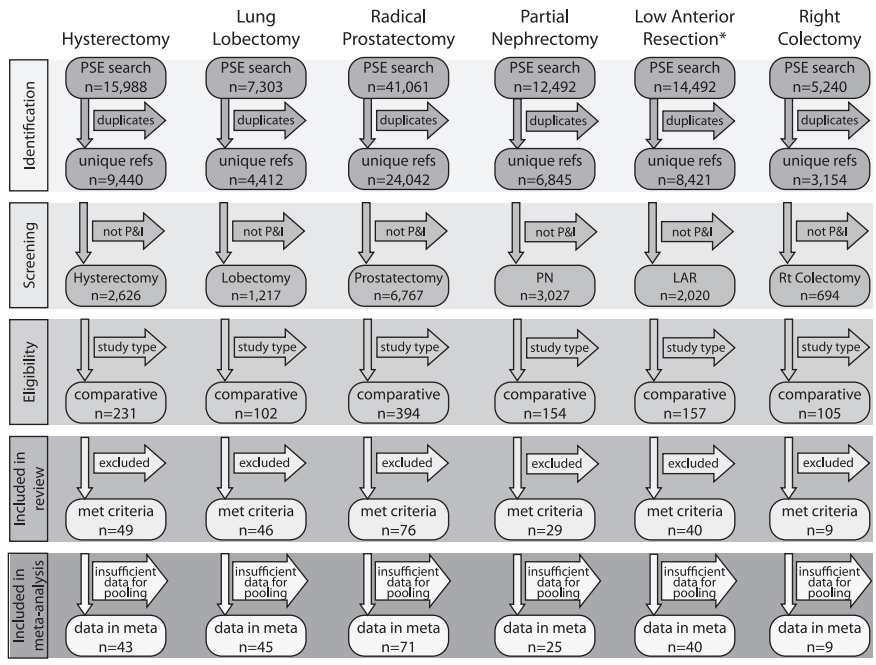

FIGURE 1. Summary PRISMA flowchart. Flowchart showing inclusion and exclusion of each paper for each procedure. *LAR group also includes total mesorectal resection and ISR. For identification, searches in each database were created using a combination of robotic, (eg, robot, robotic, robotically, "da Vinci," "intuitive surgical"), indication (eg, cancerous, malignancy, etc), anatomic (eg, prostate, renal, and uterine), and procedure (eg, nephrectomy and RC) or specialty (renal, gynecology, and urology) terms. For the screening step, articles including patients with primary, localized cancer who underwent one of the procedures of interest using da Vinci surgery were assessed. At the eligibility step, only studies published within the timeframe reporting primary clinical data (no reviews, comments, etc) and that compared da Vinci surgery to another surgical approach, with at least 20 patients in each arm were considered (no case series or case reports). Only RCTs, prospective studies, and database studies were included. Included in the review: English language studies reporting on an adult population, treated using standard surgical techniques (ie, no transanal or single-port), with the data stratified by procedure, indication, and surgical approach for at least one outcome of interest (OT, blood transfusions, estimated blood loss, conversions to open surgery, length of hospital stay, 30 days: postoperative complications, readmissions, reoperations, and mortality). Papers with redundant patient populations and similar conclusions were excluded. Included in meta-analysis: papers where mean and SD could be extracted or calculated for continuous outcomes and event n and total n could be extracted or calculated for binary data such that data could be pooled were included in the meta-analysis. Adding across columns does not equal a total number of unique papers; Shah 2022 Impact[27] is included in lung lobectomy, PN, LAR, and RC. Detailed flowcharts for each procedure that show exclusion reasons can be found in Supplementary Figs. 1–6. Details on papers that were included in the review in which data could not be pooled are listed in Supplementary Table 12 (Supplemental Digital Content Table 12, http://links.lww.com/SLA/F333). COMPARE indicates comparing perioperative outcomes of oncologic minimally invasive laparoscopic, da vinci robotic, and open procedures: a systematic review and meta-analysis of the evidence; ISR, inter sphincteric resection; LAR, low anterior resection; P&I, procedure and indication; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses; PSE, Pubmed Scopus Embase; RC, right colectomy; refs, references; TME, total mesorectal excision.

regardless of study design; however, dV-RAS cases remained less likely to receive a blood transfusion for database studies only. Length of stay was on average half a day shorter for dV-RAS cases and remained consistent regardless of study design. Postoperative complications were 9% to 23% less likely to occur among dV-RAS cases in comparison to lap/VATS and were significantly different across all 3 study designs. Readmissions and mortality within 30 days of surgery were comparable between dV-RAS and lap/VATS except among database studies [OR: 0.90 (0.82, 0.99), $P = 0.03$; OR: 0.84 (0.74, 0.96), $P < 0.01$] respectively, while 30-day reoperations were still comparable between dV-RAS and lap/VATS for all study types.

Subgroup Analysis: da Vinci Robotic-assisted Versus Open Surgery

Table 3 shows that OT was on average between 35.8 and 42.9 minutes longer for dV-RAS versus open cases across all study types and was statistically significant. Estimated blood loss and the need for blood transfusions were consistently lower for dV-RAS irrespective of study type with the exception of transfusion rates among RCTs, which while trending lower, did not reach statistical significance. Postoperative complications within 30 days of surgery were 30% to 44% less likely to occur and statistically significant in favor of dV-RAS as was the length of hospital stay which was on average between 1.6 and 2.1 days shorter for dV-RAS cases across the 3 study designs. Results for readmissions and reoperations were mixed across study types. Among database studies, a lower likelihood of readmissions and reoperations within 30 days for dV-RAS was demonstrated; 28% and 10% respectively. Further, prospective studies showed a significantly lower likelihood of 30-day reoperations for dV-RAS. Mortality within 30 days was comparable between dV-RAS and open surgery for RCT and Prospective studies and showed a 45% lower likelihood and significant difference for database studies only.

TABLE 1. Meta-analysis of Outcomes Pooled Across Surgical Procedures

Comparison	Outcome	No. of Studies	dV-RAS Sample Size	Comparator Sample Size	Weighted dV-RAS	Weighted Comparator	Weighted Effect Size (95% CI)	Effect *P*	Heterogeneity	IV Model
dV-RAS vs lap/VATS	Conversions	90	371369	593754	5.7% (5.6, 5.8)	11.6% (11.5, 11.7)	OR: 0.44 (0.40, 0.49)	**< 0.01**	$I^2 = 94\%$, $P < 0.01$	Random
	OT (min)	57	32162	51450	211.4 ± 74.0 (210.6, 212.2)	193.7 ± 63.2 (193.1, 194.2)	MD: 17.73 (9.80, 25.67)	**< 0.01**	$I^2 = 97\%$, $P < 0.01$	Random
	Blood loss (mL)	38	8421	9373	134.6 ± 134.6 (131.7, 137.5)	146.8 ± 412.6 (144.0, 149.7)	MD: -12.26 (-29.44, 4.91)	0.16	$I^2 = 94\%$, $P < 0.01$	Random
	Blood transfusions	49	113636	117991	5.1% (5.0, 5.3)	5.9% (5.7, 6.0)	OR: 0.79 (0.72, 0.88)	**< 0.01**	$I^2 = 57\%$, $P < 0.01$	Random
	Length of stay (d)	93	252632	342778	4.6 ± 3.1 (4.57, 4.59)	5.1 ± 3.4 (5.08, 5.10)	MD: -0.51 (-0.64, -0.38)	**< 0.01**	$I^2 = 98\%$, $P < 0.01$	Random
	30 d postoperative complications	74	121256	137140	25.4% (25.2, 25.7)	26.5% (26.3, 26.8)	OR: 0.90 (0.84, 0.96)	**< 0.01**	$I^2 = 76\%$, $P < 0.01$	Random
	30 d readmissions	45	248998	180708	6.5% (6.4, 6.6)	7.2% (7.0, 7.3)	OR: 0.91 (0.83, 0.99)	**0.04**	$I^2 = 80\%$, $P < 0.01$	Random
	30 d reoperations	29	27786	54186	5.0% (4.8, 5.3)	4.9% (4.7, 5.1)	OR: 1.03 (0.95, 1.11)	0.48	$I^2 = 0\%$, $P = 0.77$	Fixed
	30 d mortality	79	197886	332342	1.18% (1.13, 1.23)	1.39% (1.35, 1.43)	OR: 0.86 (0.81, 0.92)	**< 0.01**	$I^2 = 47\%$, $P < 0.01$	Fixed
							RD: -0.0015 (-0.0022, -0.0009)	**< 0.01**	$I^2 = 34\%$, $P < 0.01$	Fixed
dV-RAS vs open	OT (min)	55	62550	69876	213.9 ± 84.0 (213.2, 214.6)	173.0 ± 65.1 (172.5, 173.5)	MD: 40.92 (28.83, 53.00)	**< 0.01**	$I^2 = 99\%$, $P < 0.01$	Random
	Blood loss (mL)	44	13457	11290	174.2 ± 235.6 (170.2, 178.2)	467.6 ± 419.6 (459.9, 475.4)	MD: -293.44 (-359.53, -227.35)	**< 0.01**	$I^2 = 98\%$, $P < 0.01$	Random
	Blood transfusions	59	223564	348257	3.6% (3.5, 3.7)	11.2% (11.1, 11.3)	OR: 0.25 (0.21, 0.30)	**< 0.01**	$I^2 = 94\%$, $P < 0.01$	Random
	Length of stay (d)	84	313504	476366	4.0 ± 3.2 (3.9, 4.0)	5.8 ± 4.1 (5.80, 5.83)	MD: -1.85 (-2.09, -1.62)	**< 0.01**	$I^2 = 100\%$, $P < 0.01$	Random
	30 d postoperative complications	61	267358	324114	17.9% (17.8, 18.1)	25.2% (25.1, 25.4)	OR: 0.56 (0.52, 0.61)	**< 0.01**	$I^2 = 94\%$, $P < 0.01$	Random
	30 d readmissions	36	275302	218335	5.8% (5.7, 5.9)	7.9% (7.8, 8.1)	OR: 0.71 (0.63, 0.81)	**< 0.01**	$I^2 = 92\%$, $P < 0.01$	Random
	30 d reoperations	20	45428	177354	3.6% (3.4, 3.8)	4.15% (4.1, 4.2)	OR: 0.89 (0.81, 0.97)	**< 0.01**	$I^2 = 19\%$, $P = 0.23$	Fixed
	30 d mortality	56	333187	649982	0.93% (0.90, 0.97)	1.49% (1.46, 1.52)	OR: 0.54 (0.47, 0.63)	**< 0.01**	$I^2 = 58\%$, $P < 0.01$	Random
							RD: -0.0034 (-0.0045, -0.0022)	**< 0.01**	$I^2 = 97\%$, $P < 0.01$	Random

Bold values are statistical significance, $P < 0.05$.
Weighted values are proportion or mean, SD, and 95% CI.
IV indicates inverse variance.

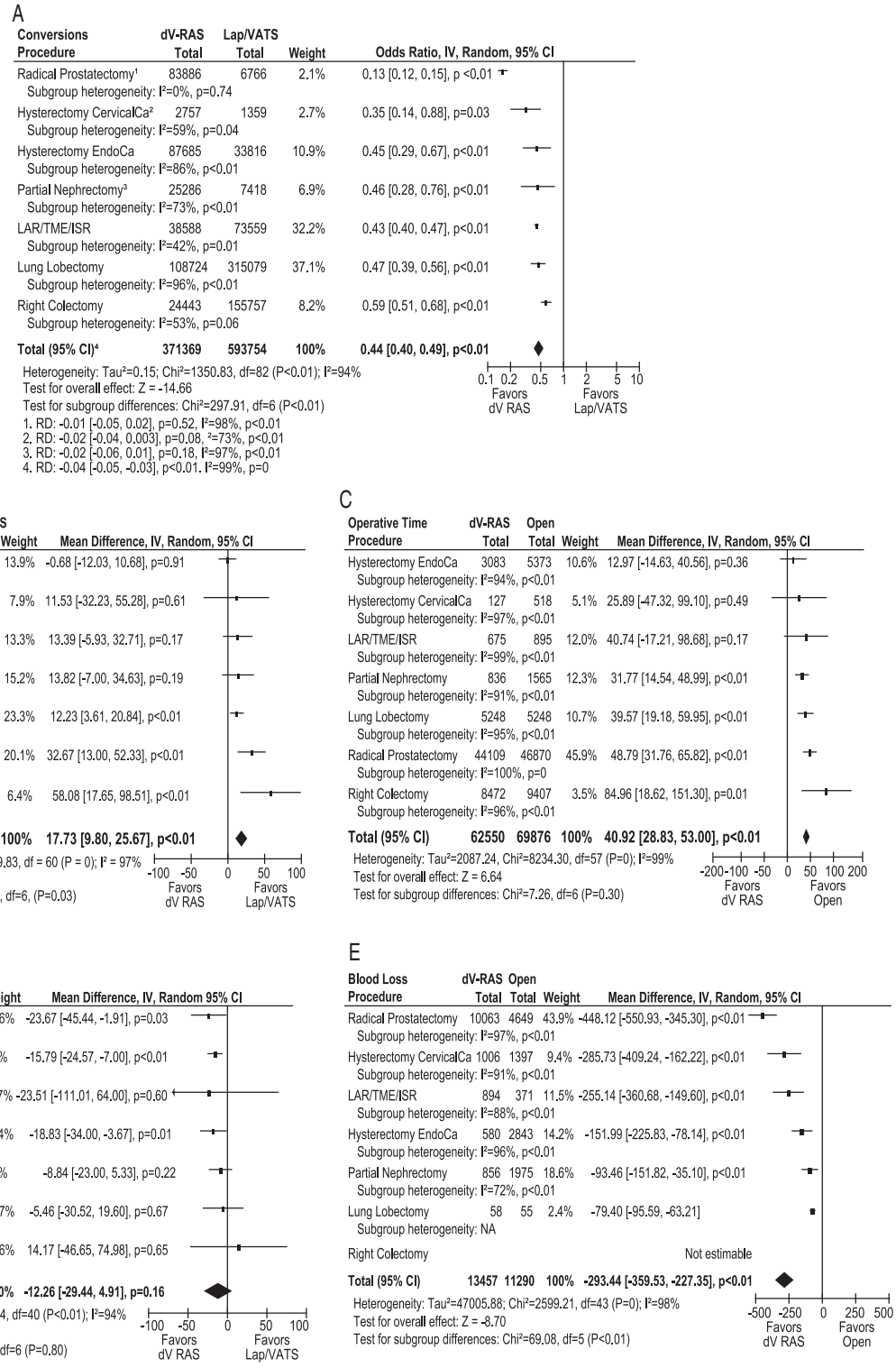

FIGURE 2. Forest plots for (A) conversions for dV-RAS versus lap/VATS, (B) OT for dV-RAS versus lap/VATS, (C) OT for dV-RAS versus open surgery, (D) blood loss for dV-RAS versus lap/VATS, and (E) blood loss for dV-RAS versus open surgery. Black squares visually represent the effect size and the black line represents the 95% CI. The black diamond represents the overall pooled effect size and its horizontal size represents the 95% CI. COMPARE indicates comparing perioperative outcomes of oncologic minimally invasive laparoscopic, da vinci robotic, and open procedures: a systematic review and meta-analysis of the evidence; df, degrees of freedom; ISR, intersphincteric resection; IV, inverse variance; LAR, low anterior resection; TME, total mesorectal excision.

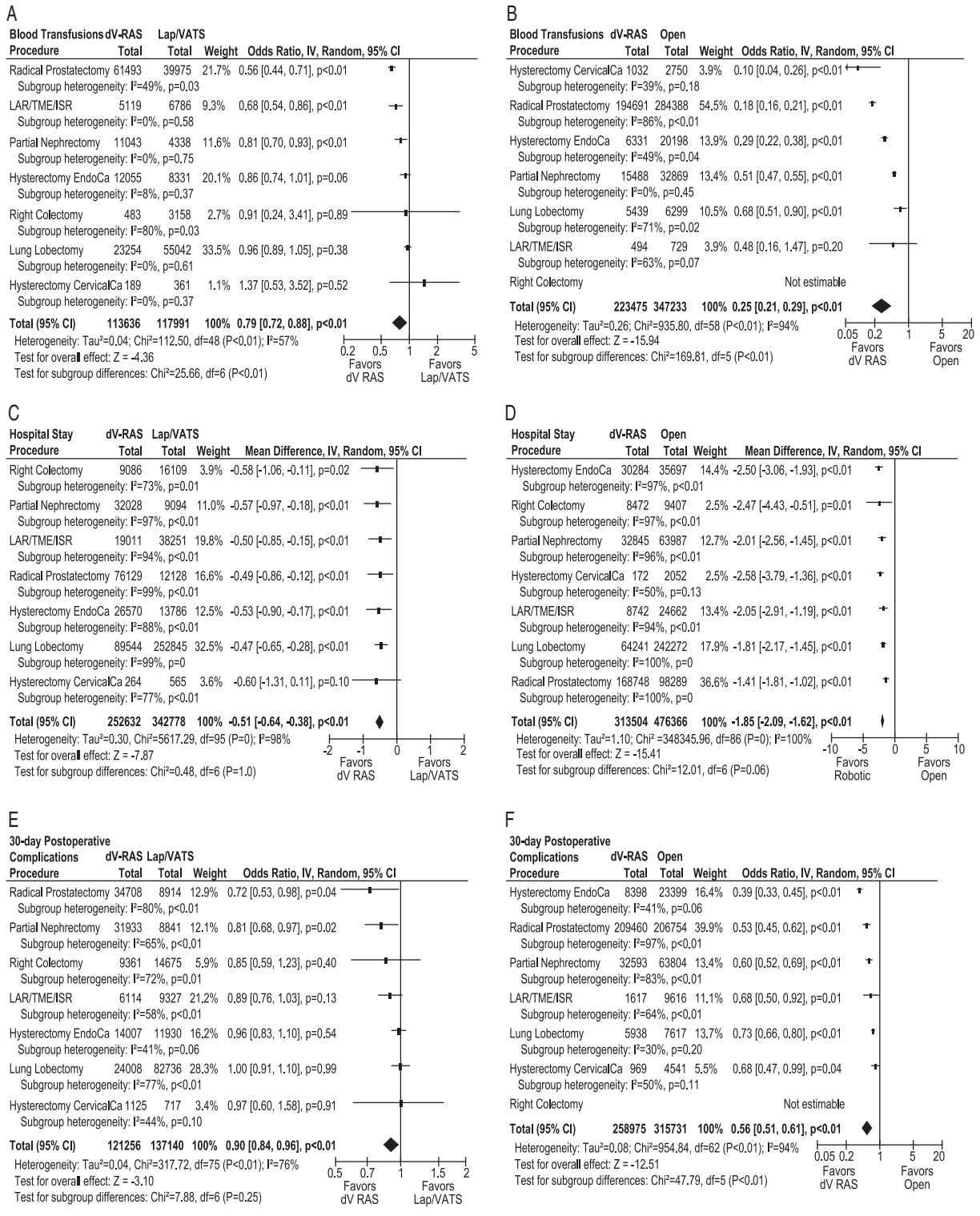

FIGURE 3. Forest plots for blood transfusions for (A) dV-RAS versus lap/VATS and (B) for dV-RAS versus open surgery, hospital stay for (C) dV-RAS versus lap/VATS and (D) dV-RAS versus open surgery, 30-day postoperative complications for (E) dV-RAS versus lap/VATS and (F) dV-RAS versus open surgery. Black squares visually represent the effect size and the black line represents the 95% CI. The black diamond represents the overall pooled effect size and its horizontal size represents the 95% CI. COMPARE indicates comparing perioperative outcomes of oncologic minimally invasive laparoscopic, da vinci robotic, and open procedures: a systematic review and meta-analysis of the evidence; df, degrees of freedom; ISR, intersphincteric resection; IV, inverse variance; LAR, low anterior resection; TME, total mesorectal excision.

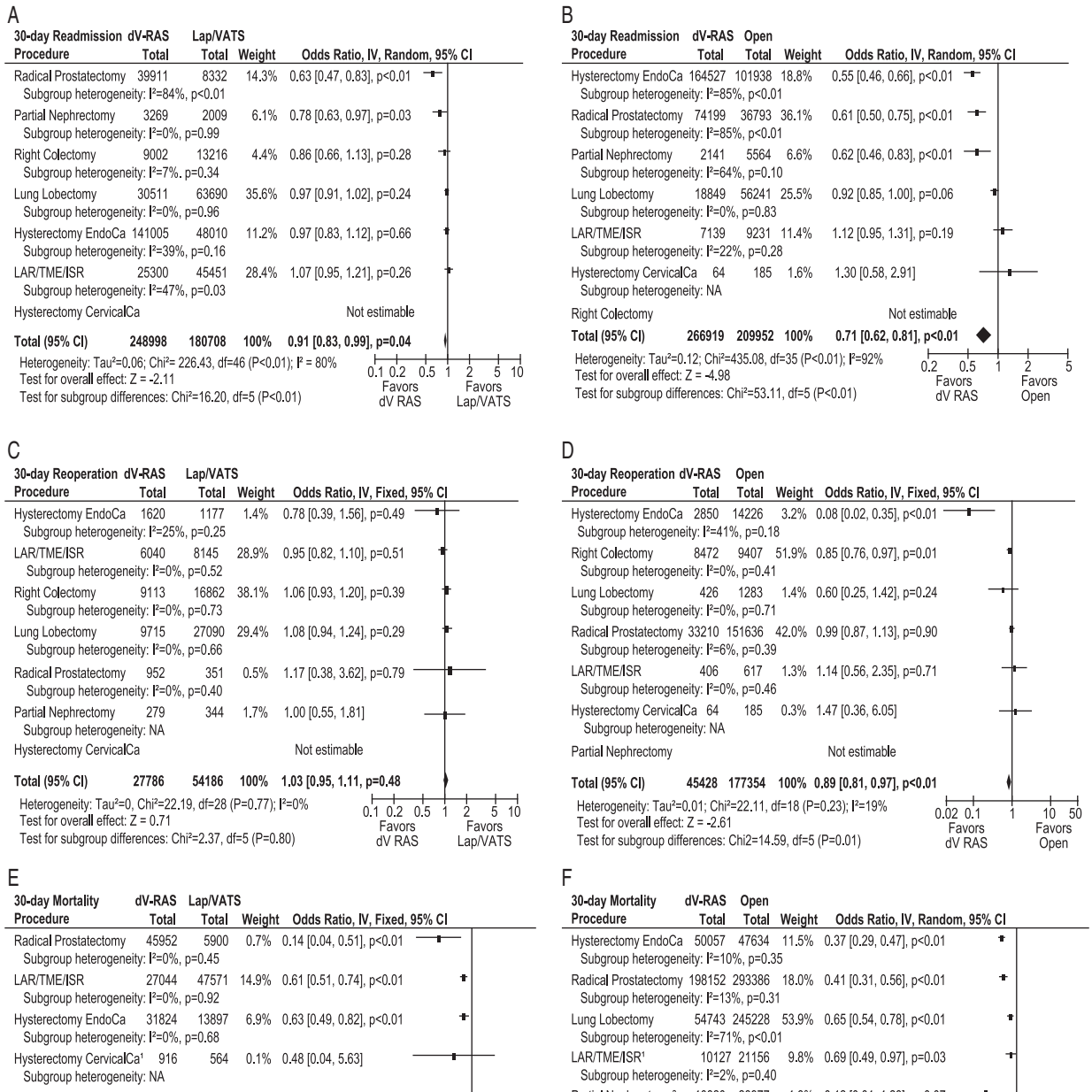

FIGURE 4. Forest plots for 30-day readmissions for (A) dV-RAS versus lap/VATS and (B) dV-RAS versus open surgery, 30-day reoperations for (C) dV-RAS versus lap/VATS, (D) dV-RAS versus open surgery, and 30-day mortality for (E) dV-RAS versus lap/VATS, and (F) dV-RAS versus open surgery. Black squares visually represent the effect size and the black line represents the 95% CI. The black diamond represents the overall pooled effect size and its horizontal size represents the 95% CI. df indicates degrees of freedom; ISR, intersphincteric resection; IV, inverse variance; LAR, low anterior resection.

TABLE 2. Subgroup Meta-analysis by Study Type: dV-RAS Versus lap/VATS

Outcome	Study Type	Procedures	No. of Studies	dV-RAS Sample Size	L/VATS Sample Size	Weighted dV-RAS Rate (95% CI) Mean ± SD	Weighted Comparator Rate (95% CI) Mean ± SD	Weighted Effect Size (95% CI)	Effect *P*	Heterogeneity	IV Model
Convert	RCT	HC/HE/L/P/PN/RC/RR	18	2384	2237	4.9% (4.0, 5.7)	8.6% (7.4, 9.7)	OR: 0.54 (0.38, 0.75)	**< 0.01**	$I^2 = 0\%$, $P = 0.74$	Fixed
	Data	HC/HE/L/P/PN/RC/RR	53	366867	588917	5.7% (5.7, 5.8)	11.9% (11.9, 12.0)	OR: 0.43 (0.38, 0.48)	**< 0.01**	$I^2 = 96\%$, $P < 0.01$	Random
	PRO	HC/HE/L/P/PN/RC/RR	20	2118	2600	4.8% (3.9, 5.7)	10.9% (9.7, 12.1)	OR: 0.56 (0.39, 0.78)	**< 0.01**	$I^2 = 19\%$, $P = 0.24$	Fixed
OT (min)	RCT	HC/HE/L/P/PN/RC/RR	22	2682	2568	199.2 ± 52.6 (197.2, 201.2)	172.4 ± 50.1 (170.4, 174.3)	MD: 26.82 (12.21, 41.42)	**< 0.01**	$I^2 = 94\%$, $P < 0.01$	Random
	Data	HE/L/P/PN/RC/RR	16	27376	47140	247.5 ± 133.0 (245.9, 249.0)	218.6 ± 98.1 (217.7, 219.4)	MD: 28.91 (15.56, 42.26)	**< 0.01**	$I^2 = 97\%$, $P < 0.01$	Random
	PRO	HC/HE/L/P/PN/RC/RR	20	2104	1742	193.8 ± 45.8 (191.8, 195.7)	194.0 ± 46.6 (191.8, 196.2)	MD: -0.27 (-9.85, 9.31)	0.96	$I^2 = 92\%$, $P < 0.01$	Random
Blood loss (mL)	RCT	HC/HE/L/P/PN/RC/RR	15	2061	2018	91.1 ± 75.8 (87.8, 94.3)	96.9 ± 83.1 (93.2, 100.5)	MD: -5.79 (-18.74, 7.15)	0.38	$I^2 = 81\%$, $P < 0.01$	Random
	Data	HE/PN/RC/RR	6	4688	5861	112.8 ± 141.3 (108.7, 116.8)	120.8 ± 174.3 (116.3, 125.2)	MD: -7.98 (-36.40, 20.43)	0.58	$I^2 = 89\%$, $P < 0.01$	Random
	PRO	HC/HE/L/P/PN/RR	17	1672	1494	170.7 ± 154.4 (163.3, 178.1)	192.2 ± 164.3 (183.8, 200.5)	MD: -21.51 (-55.38, 12.35)	0.21	$I^2 = 96\%$, $P < 0.01$	Random
BTx	RCT	HE/L/P/PN/RC/RR	9	1218	1231	5.2% (4.0, 6.5)	7.4% (5.9, 8.8)	OR: 0.72 (0.39, 1.34)	0.3	$I^2 = 23\%$, $P = 0.26$	Fixed
	Data	HC/HE/L/P/PN/RC/RR	31	111271	116013	5.0% (4.9, 5.1)	5.8% (5.7, 5.9)	OR: 0.78 (0.70, 0.87)	**< 0.01**	$I^2 = 68\%$, $P < 0.01$	Random
	PRO	HC/HE/L/P/PN	10	1147	747	5.7% (4.4, 7.0)	6.6% (4.8, 8.4)	OR: 1.05 (0.67, 1.65)	0.82	$I^2 = 0\%$, $P = 0.75$	Fixed
Hospital stay (d)	RCT	HC/HE/L/P/PN/RC/RR	16	1799	1948	5.3 ± 2.6 (5.2, 5.4)	6.0 ± 3.4 (5.8, 6.1)	MD: -0.66 (-1.12, -0.20)	**< 0.01**	$I^2 = 75\%$, $P < 0.01$	Random
	Data	HC/HE/L/P/PN/RC/RR	58	248834	339320	4.5 ± 3.5 (4.5, 4.5)	5.0 ± 3.8 (5.0, 5.0)	MD: -0.48 (-0.62, -0.34)	**< 0.01**	$I^2 = 99\%$, $P = 0$	Random
	PRO	HC/HE/L/P/PN/RR	19	1999	1510	4.6 ± 1.9 (4.5, 4.7)	5.1 ± 2.3 (5.0, 5.2)	MD: -0.51 (-0.85, -0.17)	**< 0.01**	$I^2 = 88\%$, $P < 0.01$	Random
30 d postoperative complications	RCT	HC/L/P/PN/RC/RR	15	2304	1896	20.2% (18.6, 21.9)	23.8% (21.9, 25.7)	OR: 0.85 (0.73, 0.99)	**0.03**	$I^2 = 48\%$, $P = 0.02$	Fixed
	Data	HC/HE/L/P/PN/RC/RR	39	117054	133768	25.5% (25.3, 25.8)	26.3% (26.1, 26.5)	OR: 0.91 (0.85, 0.99)	**0.02**	$I^2 = 85\%$, $P < 0.01$	Random
	PRO	HC/HE/L/P/PN/RR	19	1898	1476	27.7% (25.6, 29.7)	31.8% (29.5, 34.2)	OR: 0.81 (0.67, 0.97)	**0.02**	$I^2 = 0\%$, $P = 0.74$	Fixed
30 d readmissions	RCT	L/RR	6	1154	1106	3.7% (2.6, 4.7)	4.4% (3.2, 5.6)	OR: 1.03 (0.67, 1.58)	0.9	$I^2 = 48\%$, $P = 0.09$	Fixed
	Data	HE/L/P/PN/RC/RR	35	247609	179318	6.6% (6.5, 6.7)	7.3% (7.2, 7.4)	OR: 0.90 (0.82, 0.99)	**0.03**	$I^2 = 83\%$, $P < 0.01$	Random
	PRO	L/PN/RC	4	235	284	4.4% (1.8, 7.0)	5.1% (2.6, 7.7)	OR: 0.86 (0.37, 2.03)	0.74	$I^2 = 0\%$, $P = 0.86$	Fixed
30 d reoperations	RCT	HE/L/P/RR	8	1674	1264	4.4% (3.4, 5.4)	5.2% (4.0, 6.4)	OR: 0.82 (0.55, 1.22)	0.32	$I^2 = 0\%$, $P = 0.61$	Fixed
	Data	HC/HE/L/PN/RC/RR	12	25069	52141	5.1% (4.8, 5.3)	4.9% (4.7, 5.1)	OR: 1.04 (0.96, 1.12)	0.36	$I^2 = 0\%$, $P = 0.49$	Fixed
	PRO	HE/L/P/RC/RR	8	1043	781	4.8% (3.5, 6.1)	5.4% (3.8, 7.0)	OR: 1.02 (0.56, 1.86)	0.94	$I^2 = 0\%$, $P = 0.76$	Fixed

30 d mortality	RCT	HC/HE/L/P/RC/RR	16	2489	2099	1.3% (0.8, 1.7)	2.5% (1.8, 3.2)	OR: 0.62 (0.26, 1.47) RD: -0.002 (-0.007, 0.003)	0.28	$I^2 = 0\%$, $P = 0.95$	Fixed
									0.41	$I^2 = 0\%$, $P = 1.00$	Fixed
	Data	HC/HE/L/P/PN/RC/RR	51	194333	329220	1.1% (1.1, 1.19)	1.2% (1.2, 1.3)	OR: 0.84 (0.74, 0.96)	**<0.01**	$I^2 = 55\%$, $P < 0.01$	Random
	PRO	L/PN/RC/RR	11	1064	1023	0.5% (0.1, 1.0)	2.0% (1.1, 2.9)	OR: 0.65 (0.20, 2.11) RD: -0.002 (-0.011, 0.007)	0.47	$I^2 = 0\%$, $P = 0.63$	Fixed
									0.62	$I^2 = 0\%$, $P = 0.98$	Fixed

Bold values are statistical significance, $P < 0.05$.
BTx represents transfusions; Convert represents conversions to open; Data represents database study; PRO represents prospective comparison study.
HC indicates hysterectomy for cervical; HE, hysterectomy for endometrial; IV, inverse variance; L, lobectomy; P, prostatectomy; RC, right colectomy; RR, rectal resection.

DISCUSSION

This study evaluated dV-RAS, lap/VATS, and open surgery across 7 oncologic surgical procedures by summarizing 30-day perioperative outcomes. The results of this meta-analysis demonstrate the advantages of dV-RAS surgery for oncologic procedures, including a lower risk of conversions, blood transfusions, length of hospital stay, 30-day complications, readmissions, and mortality in comparison to lap/VATS. The advantages of dV-RAS in comparison to open surgery were seen for all outcomes studied.

Operative Time

The current meta-analysis demonstrated a longer OT between dV-RAS compared with lap/VATS and open surgery across the 7 surgical procedures. Prior multispecialty meta-analyses[18,22,23] reported longer OTs (pooled MDs ranging from 11.48[22] to 27.24 minutes longer[18]) for dV-RAS compared with laparoscopic surgery. A meta-analysis by Tan et al (2016)[23] calculated a pooled ratio of means (a unit less measure) for OT and found that robotic-assisted surgery increased OT by 7.3% compared with open surgery. The current study's finding of increased operating time between dV-RAS and laparoscopy of 17.7 minutes may represent progressive improvements in dV-RAS experience and expertise[26,28] and surgical team familiarity and efficiency with the da Vinci robotic platform (eg, draping, positioning, and docking).[29–31] It is not unusual for conventional MIS (laparoscopic/VATS) to have longer OTs when compared with open surgery, particularly for lobectomy,[32] rectal surgery,[33] colectomy,[34] prostatectomy,[35] and PN.[36] Consequently, the longer OT compared with open surgery may be more of a function of the minimally invasive surgical approach to oncologic surgery in general and less of a function of the robotic approach specifically. More importantly, the longer dV-RAS OT did not translate into compromised clinical outcomes (eg, greater conversions, blood transfusions, length of hospital stay, 30-day complications, readmissions, or reoperations).

Conversions

The dV-RAS group had a 56% lower risk of conversion to laparotomy compared with lap/VATS, which is one of the most consistent findings, with each procedure and each study type independently significant. An earlier meta-analysis of RCTs by Roh et al[22] that included benign and cancer procedures, reported no difference in conversions between robotic-assisted and laparoscopic surgery. However, the authors also included conversions to laparoscopy, which were often due to issues unrelated to the surgery and had more to do with inexperience with the robotic system. An analysis of the same papers (excluding the AESOP paper that was not robotic) looking at just conversions to laparotomy, results in a significantly lower conversion rate for robotic surgery [3/541 (0.6%) vs 22/544 (4.0%); OR: 0.22 (0.09, 0.54), $P < 0.01$; heterogeneity $I^2 = 0\%$; χ^2, $P = 0.72$; RD: -0.04 (-0.06, -0.01), $P < 0.01$; heterogeneity $I^2 = 19\%$; χ^2, $P = 0.22$] showing consistency with our findings. The conversion to laparotomy rate is a measure of the surgical effectiveness of a minimally invasive procedure and is clinically significant because it is typically associated with increased blood loss, higher rates of intraoperative and postoperative complications, longer hospital stays, increased health care costs[37–40] and ultimately denies the patient the benefits of MIS. The cost paper by Cleary et al (2018)[38] reported an adjusted episode payment savings of $2580 for

TABLE 3. Subgroup Meta-analysis by Study Type: dV-RAS Versus Open

Outcome	Study Type	Procedures	No. of Studies	dV-RAS Sample Size	Open Sample Size	Weighted dV-RAS Rate (95% CI) Mean ± SD	Weighted Comparator Rate (95% CI) Mean ± SD	Weighted Effect size (95% CI)	Effect *P*	Heterogeneity	IV Model
OT (min)	RCT	HC/HE/L/P/RR	7	748	701	196.3 ± 45.7 (193.0, 199.6)	160.5 ± 38.5 (157.7, 163.4)	MD: 35.79 (2.82, 68.76)	**0.03**	$I^2 = 98\%$, $P < 0.01$	Random
	Data	HC/HE/L/P/PN/RC/RR	15	54913	64487	220.4 ± 123.2 (219.4, 221.4)	181.6 ± 87.9 (180.9, 182.3)	MD: 38.80 (24.62, 52.97)	**< 0.01**	$I^2 = 99\%$, $P = 0$	Random
	PRO	HC/HE/L/P/PN/RR	33	6889	4688	214.4 ± 71.0 (212.7, 216.1)	171.5 ± 59.0 (169.8, 173.2)	MD: 42.86 (24.01, 61.71)	**< 0.01**	$I^2 = 98\%$, $P = 0$	Random
Blood loss (mL)	RCT	HC/HE/L/P/RR	8	755	709	142.2 ± 99.0 (135.2, 149.3)	365.8 ± 230.4 (348.8, 382.7)	MD: -223.5 (-413.9, -33.2)	**0.02**	$I^2 = 98\%$, $P < 0.01$	Random
	Data	HC/HE/P/PN/RR	7	5034	5579	137.9 ± 171.4 (133.2, 142.6)	425.0 ± 436.4 (413.5, 436.4)	MD: -287.1 (-427.7, -146.5)	**< 0.01**	$I^2 = 99\%$, $P < 0.01$	Random
	PRO	HC/HE/P/PN/RR	29	7668	5002	192.7 ± 291.3 (186.2, 199.2)	508.4 ± 469.0 (495.4, 521.4)	MD: -315.6 (-395.6, -235.7)	**< 0.01**	$I^2 = 97\%$, $P < 0.01$	Random
BTx	RCT	HE/P	5	669	417	0.4% (0.0, 0.9)	3.4% (1.7, 5.2)	OR: 0.32 (0.09, 1.08)	0.07	$I^2 = 0\%$, $P = 0.67$	Fixed
	Data	HC/HE/L/P/PN/RC/RR	32	215529	342891	3.7% (3.6, 3.7)	10.5% (10.4, 10.6)	OR: 0.25 (0.21, 0.31)	**< 0.01**	$I^2 = 96\%$, $P < 0.01$	Random
	PRO	HC/HE/P/PN/RR	22	7366	4949	3.8% (3.4, 4.2)	17.7% (16.6, 18.7)	OR: 0.21 (0.18, 0.25)	**< 0.01**	$I^2 = 20\%$, $P = 0.2$	Fixed
Hospital stay (d)	RCT	HC/HE/L/P/RR	8	773	726	3.5 ± 2.3 (3.4, 3.7)	5.7 ± 3.1 (5.5, 5.9)	MD: -2.14 (-3.58, -0.70)	**< 0.01**	$I^2 = 98\%$, $P < 0.01$	Random
	Data	HC/HE/L/P/PN/RC/RR	50	305941	471036	3.8 ± 3.5 (3.8, 3.9)	5.8 ± 4.6 (5.8, 5.8)	MD: -1.93 (-2.18, -1.69)	**< 0.01**	$I^2 = 100\%$, $P = 0$	Random
	PRO	HE/L/P/PN/RR	26	6790	4604	4.3 ± 2.9 (4.3, 4.4)	6.0 ± 3.3 (5.9, 6.1)	MD: -1.62 (-2.09, -1.15)	**< 0.01**	$I^2 = 96\%$, $P < 0.01$	Random
30 d postoperative complications	RCT	HE/L/P/RR	7	714	452	16.2% (13.5, 18.9)	22.4% (18.5, 26.2)	OR: 0.70 (0.50, 0.98)	**0.04**	$I^2 = 43\%$, $P = 0.10$	Fixed
	Data	HC/HE/L/P/PN/RC/RR	36	264054	322060	18.3% (18.1, 18.4)	25.7% (25.5, 25.8)	OR: 0.56 (0.51, 0.62)	**< 0.01**	$I^2 = 96\%$, $P < 0.01$	Random
	PRO	HC/HE/L/P/PN/RR	18	2590	1602	15.6% (14.2, 17.0)	22.0% (20.0, 24.0)	OR: 0.58 (0.39, 0.87)	**< 0.01**	$I^2 = 74\%$, $P < 0.01$	Random
30 d readmissions	RCT	HE/P	3	581	323	5.3% (3.5, 7.2)	7.2% (4.4, 10.1)	OR: 0.86 (0.47, 1.59)	0.64	$I^2 = 0\%$, $P = 0.37$	Fixed
	Data	HC/HE/L/P/PN/RC/RR	28	273719	217222	5.9% (5.8, 6.0)	8.0% (7.9, 8.1)	OR: 0.72 (0.63, 0.82)	**< 0.01**	$I^2 = 93\%$, $P < 0.01$	Random
	PRO	HE/P/RR	5	1002	790	3.7% (2.5, 4.8)	8.5% (6.6, 10.4)	OR: 0.35 (0.08, 1.49)	0.15	$I^2 = 80\%$, $P < 0.01$	Random
30 d reoperations	RCT	HE/L	2	106	103	1.9% (0.0, 4.5)	1.9% (0.0, 4.6)	OR: 0.97 (0.13, 7.04)	0.98	$I^2 = 0\%$, $P = 0.98$	Fixed
	Data	HC/HE/L/P/RC/RR	8	41212	175480	3.7% (3.5, 3.9)	4.2% (4.1, 4.3)	OR: 0.90 (0.83, 0.99)	**0.03**	$I^2 = 46\%$, $P = 0.06$	Fixed
	PRO	L/P/RR	10	4110	1771	1.5% (1.1, 1.8)	3.2% (2.4, 4.0)	OR: 0.58 (0.37, 0.92)	**0.02**	$I^2 = 0\%$, $P = 0.83$	Fixed

30 d mortality	RCT	HE/L/P/RR	5	664	403	1.7%* (0.7, 2.7)	0% (0.0, 0.0)	OR: 2.90 (0.12, 72.60) RD: 0.002 (-0.008, 0.012)	0.52 0.69	NA $I^2 = 0\%$, $P = 0.96$	Fixed Fixed
	Data	HC/HE/L/P/PN/RC/RR	40	328283	647214	0.9% (0.9, 1.0)	1.5% (1.5, 1.5)	OR: 0.55 (0.47, 0.63)	**< 0.01**	$I^2 = 60\%$, $P < 0.01$	Random
	PRO	P/PN/RR	11	4240	2365	0% (0, 0)	0.8% (0.5, 1.2)	OR: 0.12 (0.01, 1.13) RD: -0.001 (-0.004, 0.002)	0.06 0.47	$I^2 = 0\%$, $P = 0.93$ $I^2 = 0\%$, $P = 1.00$	Fixed Fixed

Bold values are statistical significance, $P < 0.05$.
BTx represents transfusions; Convert represents conversions to open; Data represents database study; PRO represents prospective comparison study.
*Weighted proportion is based on the OR test (RD is 0.2%); there was a single death in the robotic group.
HC indicates hysterectomy for cervical; HE, hysterectomy for endometrial; IV, inverse variance; L, lobectomy; NA, not available; P, prostatectomy; RC, right colectomy; RR, rectal resection.

patients avoiding a conversion, which would translate into a savings of $152,220 per 1000 patients using the overall estimate for conversions from our meta-analysis (5.7% dV-RAS vs 11.6% lap/VATS) and a savings of $95,460 per 1000 patients using the RCT subgroup analysis estimate (4.9% dV-RAS vs 8.6% lap/VATS).

Estimate Blood Loss/Blood Transfusions

The dV-RAS blood transfusion risk was 21% lower compared with traditional lap/VATS and 75% lower compared with open surgery. These findings are consistent with pooled analysis of RCT and prospective non-randomized studies (1998–2014) by Tan et al[23] comparing transfusions for robotic-assisted surgery and MIS (13 studies) or open (17 studies) surgery but differ from meta-analyses by Roh et al[22] who reported no difference in transfusion rate between robotic-assisted surgery and laparoscopic surgery in an analysis of 4 RCTs. This is most likely because their sample size was too small to detect the difference versus conventional laparoscopy. Our main analysis of transfusions included 49 studies; our study type subgroup analysis showed significance only in the database study group, even though all study types had a lower transfusion rate in the robotic group. The most notable differences were identified when comparing robotics to open surgery, where the benefits of robotic surgery could have the greatest clinical impact. Excessive perioperative blood loss is a major surgical complication that is often managed with blood transfusion and in some instances reoperation.[41] Intraoperatively, bleeding hampers surgeon visibility, agility, and precision within the operative field.[42] A 2014 American College of Surgeons National Surgical Quality Improvement Program database analysis found perioperative blood transfusion to be independently associated with an increased risk of morbidity and mortality after most major abdominal operations.[43] In addition, surgical patients who experienced a bleeding-related complication and/or received a blood transfusion had a longer stay in the intensive care unit (overall mean: 3.3 vs 0.5 days), overall hospital stay (overall mean: 10.4 vs 4.4 days), resulting in higher mean inpatient costs than patients who did not have a bleeding complication or blood transfusion (by $13,210 for solid organ surgery).[41] The blood transfusion estimate for robotic (3.6%) versus open (11.2%) results in a 7.6% difference, which would translate into a robotic cost savings of $1,003,960 for every 1000 solid organ surgery patients. This is consistent with a 2010 prospective study from 2 American and 2 European hospitals that reported annual costs for blood and transfusion-related activities (eg, staff time, supplies, and direct and indirect overhead costs) in surgical patients ranged between $1.62 and $6.03 million per hospital.[44]

Thirty-day Postoperative Complications

The dV-RAS 30-day complication risk was 10% less compared with lap/VATS and 44% less compared with those undergoing open surgery. This finding is consistent with the robotic versus open analysis of 30-day overall complications [11.6% (515/4453) all robot types vs 21.4% (693/3245) open] in the meta-analysis by Tan 2016[23] but is in contrast to other robotic versus laparoscopic meta-analyses that reported comparable 30-day overall complications,[23] total complications,[18] intraoperative complications,[22] postoperative complications,[22] or greater total complications.[22] This is most likely due to the inclusion of benign procedures and a

smaller sample size in these other studies. It is well documented that postoperative complications increase health care costs,[45–47] and health care expenditures increase with postoperative complication severity.[48] A National Inpatient Sample database study of patients who underwent major gastrointestinal resections for malignancy between 2001 and 2014 reported any in-hospital complication increased index hospital costs by an average of $20,900 (95% CI: $20,300–21,500).[49] This would translate into a savings of $1,525,700 for dV-RAS versus open surgery based on 30-day postoperative complication rates of 17.9% dV-RAS, and 25.2% open (Table 1). In addition, patients who had a complication stayed in the hospital an average of 5.5 days longer, were 3 times more likely to require a non-routine discharge, and at 6 times higher risk of in-hospital death compared with patients who did not have a complication.[49] For the patient, postoperative complications are also associated with reduced quality of life and decreased satisfaction with their surgical and postoperative experience.[50] Postoperative complication rates are indicators of surgical and hospital quality. Therefore, the implementation of interventions associated with reduced complications, such as dV-RAS, may provide greater value-based care to both patients and hospitals.

Length of Hospital Stay

The hospital stay for the dV-RAS group was on average half a day shorter compared with lap/VATS and almost 2 days shorter than open surgery, a finding that was seen consistently across all procedures and all study types. Differences in discharge protocols can confound comparisons in hospital stay; however, RCT and prospective studies specifically control for these types of differences. In addition, systematic differences in discharge criteria (such as for U.S. vs non-U.S. institutions) do not affect a pooled MD per se because the difference should influence hospital stay for both the robotic and comparator cohorts relatively equally within an institution. For example, if a European hospital requires patients to be off of a catheter after prostatectomy surgery before discharging that patient, it would require both robotic patients and laparoscopic patients to be catheter-free.

Previously published meta-analyses found no difference in length of hospital stay between robotic-assisted and laparoscopic surgery across surgical procedures.[18,22,23] The RCT meta-hospital stay analysis by Broholm et al (2016)[18] included 70% of benign studies (only 3 cancer papers) and the majority of studies were published before 2010, with only 1 paper overlapping with our study.[51] The RCT meta by Roh et al (2018)[22] also included benign and cancer studies mixed in the analysis, and limiting their analysis to cancer papers would also result in a shorter hospital stay for the robotic group [MD: -1.04 (-1.32, -0.76), $P < 0.00001$, $I^2 = 46\%$, χ^2, $P = 0.08$ fixed model]. Tan 2016[23] also mixed benign and cancer procedures in the hospital stay analysis and included studies published before 2010. However, a more recent meta-analysis by Choi et al 2024 also found significantly shorter hospital stays with dV-RAS compared with traditional laparoscopy.[19] This meta did mix benign and cancer papers, which may be why they found a shorter difference of a quarter of a day. Tan et al reported a shorter hospital stay for robotic-assisted surgery compared with open surgery across surgical procedures.[23] Length of hospital stay is an indicator of hospital efficiency[52] and quality of care.[53] Hospitals with the shortest length of stays for common surgical procedures have lower costs, fewer postoperative complications, higher surgical volumes, and greater use of MIS.[53] Prior research has shown that shorter hospital stays are not associated with increased post-discharge care spending (i.e. no increased payments for readmissions or physician services) for older adults undergoing major surgery.[53] Given that in 2018, inpatient care in the United States averaged $2,517 per day[54,55] even modest improvements in the length of hospital stay, such as half of a day, can translate into large health care cost savings. Assuming a single surgeon's annual case volume of 200 procedures, a half-day shorter hospital stay would translate into a savings of $251,700 and a 1.8-day shorter hospital stay (robotic vs. open surgery) would save $906,120.

Thirty-day Readmissions, Reoperations, and Mortality

An American College of Surgeons National Surgical Quality Improvement Program study found that surgery-related complications were the most common reason for 30-day unplanned readmissions in surgical patients. The 3 leading causes of readmission were surgical site infection, ileus or obstruction, and bleeding.[56] In addition, although experiencing an inpatient complication was related to an unplanned hospital readmission, most readmissions were attributable to a new surgery-related complication.[56] Ejaz et al (2016)[45] reported that 30-day readmission after a major abdominal surgery increased the total index hospitalization costs by $4991 for all patients (readmission: $29,312 vs no readmission: $24,321; $P < 0.001$) and by $4337 for patients who did not have an inpatient complication (readmission: $26,799 vs no readmission: $22,462; $P < 0.001$). Regardless of the reason, health care costs are increased when surgical patients require readmissions. Although absent from prior multispecialty meta-analyses,[18,22,23] the current study evaluated readmissions, reoperations, and mortality within 30 days of surgery. Readmissions and mortality were both lower in the dV-RAS group versus both lap/VATS and versus open surgery, whereas reoperations were only different versus open surgery. These 30-day outcomes are meaningful, as ~25% of postoperative deaths occur after hospital discharge,[57] while readmissions are associated with increased risk of postoperative mortality in high-risk surgical patients (eg, colectomy, lobectomy),[58] and prolonged physical functional recovery in older surgical patients.[59] Furthermore, this demonstrates that dV-RAS's shorter length of stay did not translate into greater rates of hospital readmission or postoperative mortality.

Limitations

A first limitation of this meta-analysis may be the potential bias from the inclusion of studies with non-randomized prospective and database study designs. To account for this potential bias, subgroup analyses were performed to assess the effect of study design on the summary effect size of perioperative outcomes,[60] including an analysis limited to RCTs. The benefits of decreased hospital stay, fewer conversions, and fewer 30-day postoperative complications for dV-RAS versus conventional laparoscopy were seen across all study types, including in the RCT subgroup analysis, demonstrating the robustness of these results. RCTs are traditionally used in meta-analyses as they minimize bias; however, bias is also present in surgical RCTs because of the impracticality of standardizing surgical technique, different surgeons performing

robotic, laparoscopic, and open surgery, often with differing experience levels, and the lack of ability to blind surgeons, patients, or nurses providing care and assessing outcomes. RCTs also suffer from limitations relating to small sample sizes, which limits the ability to detect differences with rare events and often results in outcomes that could change in significance with the addition of more patients.[61] Furthermore, the surgical literature contains relatively few RCTs due to the inherent difficulties and expenses of conducting surgical trials. Although potential biases are likely to be greater for nonrandomized studies, they can complement the limited surgical RCT literature by providing context and generalizability in assessing the effectiveness of surgical approaches with real-world surgeons and patient populations that are larger and more diverse.[62] Second, perioperative outcomes were aggregated despite differences in operational definitions. In studies, perioperative outcomes were frequently stated, but were less frequently defined and when defined, the terminology was consistent within a study but often differed across studies (eg, OT, total OT, skin-to-skin, and wheels-in-to-wheels-out) complicating the aggregation of outcomes by each definition. In an attempt to make use of available data, this meta-analysis did not discern between intra-study differences in perioperative outcome definitions. While recognizing that this methodological decision may introduce variability, the inclusion of only comparative studies ensures that the perioperative definition inconsistency would be similarly inconsistent across surgical cohorts. Third, significant heterogeneity was observed for the majority of outcomes in the main analysis, most likely due to study type and procedure differences resulting in differences in effect sizes between studies.[60] The subgroup analysis by study type showed less heterogeneity within a study type; however, there can still be differences between studies due to procedure characteristics (such as type and severity of disease and differences in the extent of resection), surgeon characteristics, such as experience level, and patient characteristics. When heterogeneity was present, a random-effect model was used which may have contributed to lower confidence in the summary estimates. Fourth, the results of this COMPARE study are applicable to the 7 included oncologic surgical procedures and to perioperative outcomes and may not be generalizable to all procedures or to oncological outcomes, as that was not the focus of this paper. The procedures were chosen as representative of complex and commonly performed da Vinci surgeries and the outcomes chosen represent safety and effectiveness measures. A separate meta-analysis of long-term oncological outcomes for 5 of the 7 procedures in this study was recently published by Leitao et al[25] demonstrating similar or improved oncologic outcomes for dV-RAS.

Future Directions

While this work focused on clinical outcomes from oncological procedures performed using the da Vinci Surgical System (all multiport models) compared with laparoscopy and open surgery, there have been advances in the area of robotic technology. Recently, the next generation da Vinci robotic system dV5 received clearance from the U.S. FDA and now includes haptic feedback and ergonomic improvements to the surgeon console. In addition, numerous competitive platforms have been introduced to the global market. Adoption of these new devices in general surgery is constantly growing with the extension of regulatory approvals. However, standardization of the training process and the assessment of skill transferability is still lacking.[63] Future studies will be required to better understand their clinical and economic benefits.

CONCLUSIONS

This meta-analysis covering 12 years of peer-reviewed literature across 7 oncologic surgeries, demonstrates multiple benefits for dV-RAS as compared with both lap/VATS and open surgery. The strengths of this meta-analysis include the use of multiple study designs (RCTs, prospective, and real-world evidence), the evaluation of perioperative outcomes in several complex oncologic operations, and the expansion of the utility of the results to those interested in individual or collective procedures. The results of this study will be helpful to decision-makers considering the use of robotics in a multispecialty-care setting.

ACKNOWLEDGMENTS

The authors thank Hannah Bossie, Param Vaidya, and Faye Routeledge for their help with literature research, reviews, and data extraction.

REFERENCES

1. Bogani G, Rossetti D, Ditto A, et al. Minimally invasive surgery improves short-term outcomes of nerve-sparing radical hysterectomy in patients with cervical cancer: a propensity-matched analysis with open abdominal surgery. *J Gynecol Oncol*. 2019;30:e27.
2. Buia A, Stockhausen F, Hanisch E. Laparoscopic surgery: a qualified systematic review. *World J Methodol*. 2015;5:238–254.
3. Casarin J, Multinu F, Ubl DS, et al. Adoption of minimally invasive surgery and decrease in surgical morbidity for endometrial cancer treatment in the United States. *Obstet Gynecol*. 2018;131:304–311.
4. Martinez-Perez A, Carra MC, Brunetti F, et al. Short-term clinical outcomes of laparoscopic vs open rectal excision for rectal cancer: a systematic review and meta-analysis. *World J Gastroenterol*. 2017;23:7906–7916.
5. Vargas GM, Sieloff EP, Parmar AD, et al. Laparoscopy decreases complications for obese patients undergoing elective rectal surgery. *Surg Endosc*. 2016;30:1826–1832.
6. Ashrafian H, Clancy O, Grover V, et al. The evolution of robotic surgery: surgical and anaesthetic aspects. *Br J Anaesth*. 2017;119(suppl 1):i72–i84.
7. Norasi H, Hallbeck MS, Elli EF, et al. Impact of preferred surgical modality on surgeon wellness: a survey of workload, physical pain/discomfort, and neuromusculoskeletal disorders. *Surg Endosc*. 2023;37:9244–9254.
8. Perez RE, Schwaitzberg SD. Robotic surgery: finding value in 2019 and beyond. *Ann Laparosc Endosc Surg*. 2019;4:51.
9. Intuitive Surgical. Intuitive da Vinci: World class robotic surgical systems; 2020. Accessed April 03, 2020. https://www.intuitive.com/en-us/products-and-services/da-vinci/systems
10. Patton MW, Salevitz DA, Tyson MD, et al. Robot-assisted partial nephrectomy for complex renal masses. *J Robot Surg*. 2016;10:27–31.
11. Ricciardi S, Zirafa CC, Davini F, et al. How to get the best from robotic thoracic surgery. *J Thorac Dis*. 2018;10(suppl 8):S947–S950.
12. Sinha R, Sanjay M, Rupa B, et al. Robotic surgery in gynecology. *J Minim Access Surg*. 2015;11:50–59.
13. Addae JK, Gani F, Fang SY, et al. A comparison of trends in operative approach and postoperative outcomes for colorectal cancer surgery. *J Surg Res*. 2017;208:111–120.

14. Beck TL, Schiff MA, Goff BA, et al. Robotic, laparoscopic, or open hysterectomy: surgical outcomes by approach in endometrial cancer. *J Minim Invasive Gynecol*. 2018;25:986–993.
15. De Carlo F, Celestino F, Verri C, et al. Retropubic, laparoscopic, and robot-assisted radical prostatectomy: surgical, oncological, and functional outcomes: a systematic review. *Urol Int*. 2014;93:373–383.
16. Kent M, Wang T, Whyte R, et al. Open, video-assisted thoracic surgery, and robotic lobectomy: review of a national database. *Ann Thorac Surg*. 2014;97:236–242; discussion 242–234.
17. Somashekhar SP, Ashwin KR, Rajashekhar J, et al. Prospective randomized study comparing robotic-assisted surgery with traditional laparotomy for rectal cancer Indian study. *Indian J Surg*. 2015;77(suppl 3):788–794.
18. Broholm M, Onsberg Hansen I, Rosenberg J. Limited evidence for robot-assisted surgery: a systematic review and meta-analysis of randomized controlled trials. *Surg Laparosc Endosc Percutan Tech*. 2016;26:117–123.
19. Choi JH, Diab AR, Tsay K, et al. The evidence behind robot-assisted abdominopelvic surgery: a meta-analysis of randomized controlled trials. *Surg Endosc*. 2024;38:2371–2382.
20. Dhanani NH, Olavarria OA, Bernardi K, et al. The evidence behind robot-assisted abdominopelvic surgery: a systematic review. *Ann Intern Med*. 2021;174:1110–1117.
21. Guerra F, Giuliani G, Coletta D. The risk of conversion in minimally invasive oncological abdominal surgery. Meta-analysis of randomized evidence comparing traditional laparoscopic versus robot-assisted techniques. *Langenbecks Arch Surg*. 2021;406:607–612.
22. Roh HF, Nam SH, Kim JM. Robot-assisted laparoscopic surgery versus conventional laparoscopic surgery in randomized controlled trials: a systematic review and meta-analysis. *PLoS One*. 2018;13:e0191628.
23. Tan A, Ashrafian H, Scott AJ, et al. Robotic surgery: disruptive innovation or unfulfilled promise? A systematic review and meta-analysis of the first 30 years. *Surg Endosc*. 2016;30:4330–4352.
24. Moher D, Liberati A, Tetzlaff J, et al. Group P. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS Med*. 2009;6:e1000097.
25. Leitao MM Jr, Kreaden US, Laudone V, et al. The RECOURSE study: long-term oncologic outcomes associated with robotically assisted minimally invasive procedures for endometrial, cervical, colorectal, lung, or prostate cancer: a systematic review and meta-analysis. *Ann Surg*. 2023;277:387–396.
26. Lim PC, Kang E, Park DH. Learning curve and surgical outcome for robotic-assisted hysterectomy with lymphadenectomy: case-matched controlled comparison with laparoscopy and laparotomy for treatment of endometrial cancer. *J Minim Invasive Gynecol*. 2010;17:739–748.
27. Shah PC, de Groot A, Cerfolio R, et al. Impact of type of minimally invasive approach on open conversions across ten common procedures in different specialties. *Surg Endosc*. 2022;36:6067–6075.
28. Nayyar R, Yadav S, Singh P, et al. Impact of assistant surgeon on outcomes in robotic surgery. *Indian J Urol*. 2016;32:204–209.
29. Lasser MS, Patel CK, Elsamra SE, et al. Dedicated robotics team reduces pre-surgical preparation time. *Indian J Urol*. 2012;28:263–266.
30. Mantoo S, Rigaud J, Naulet S, et al. Standardized surgical technique and dedicated operating room environment can reduce the operative time during robotic-assisted surgery for pelvic floor disorders. *J Robot Surg*. 2014;8:7–12.
31. van der Schans EM, Hiep MAJ, Consten ECJ, et al. From Da Vinci Si to Da Vinci Xi: realistic times in draping and docking the robot. *J Rob Surg*. 2020;14:835–839.
32. Wang Z, Pang L, Tang J, et al. Video-assisted thoracoscopic surgery versus muscle-sparing thoracotomy for non-small cell lung cancer: a systematic review and meta-analysis. *BMC Surg*. 2019;19:144.
33. Chen K, Cao G, Chen B, et al. Laparoscopic versus open surgery for rectal cancer: a meta-analysis of classic randomized controlled trials and high-quality Nonrandomized Studies in the last 5 years. *Int J Surg*. 2017;39:1–10.
34. Wu Q, Wei M, Ye Z, et al. Laparoscopic colectomy versus open colectomy for treatment of transverse colon cancer: a systematic review and meta-analysis. *J Laparoendosc Adv Surg Tech A*. 2017;27:1038–1050.
35. Alessandro S, Alessandro G, Susanna C, et al. Laparoscopic versus open radical prostatectomy in high prostate volume cases: impact on oncological and functional results. *Int Braz J Urol*. 2016;42:223–233.
36. Rezaeetalab GH, Karami H, Dadkhah F, et al. Laparoscopic versus open partial nephrectomy for stage T1a of renal tumors. *Urol J*. 2016;13:2903–2907.
37. Bongiolatti S, Gonfiotti A, Viggiano D, et al. Risk factors and impact of conversion from VATS to open lobectomy: analysis from a national database. *Surg Endosc*. 2019;33:3953–3962.
38. Cleary RK, Mullard AJ, Ferraro J, et al. The cost of conversion in robotic and laparoscopic colorectal surgery. *Surg Endosc*. 2018;32:1515–1524.
39. Sharma V, Meeks JJ. Open conversion during minimally invasive radical prostatectomy: impact on perioperative complications and predictors from national data. *J Urol*. 2014;192:1657–1662.
40. Yamamoto S, Fukunaga M, Miyajima N, et al. Impact of conversion on surgical outcomes after laparoscopic operation for rectal carcinoma: a retrospective study of 1,073 patients. *J Am Coll Surg*. 2009;208:383–389.
41. Stokes ME, Ye X, Shah M, et al. Impact of bleeding-related complications and/or blood product transfusions on hospital costs in inpatient surgical patients. *BMC Health Serv Res*. 2011;11:135.
42. McAlpine K, Forster AJ, Breau RH, et al. Robotic surgery improves transfusion rate and perioperative outcomes using a broad implementation process and multiple surgeon learning curves. *Can Urol Assoc J*. 2019;13:184–189.
43. Elwood NR, Martin AN, Turrentine FE, et al. The negative effect of perioperative red blood cell transfusion on morbidity and mortality after major abdominal operations. *Am J Surg*. 2018;216:487–491.
44. Shander A, Hofmann A, Ozawa S, et al. Activity-based costs of blood transfusions in surgical patients at four hospitals. *Transfusion (Paris)*. 2010;50:753–765.
45. Ejaz A, Gonzalez AA, Gani F, et al. Effect of index hospitalization costs on readmission among patients undergoing major abdominal surgery. *JAMA Surg*. 2016;151:718–724.
46. Pradarelli JC, Healy MA, Osborne NH, et al. Variation in medicare expenditures for treating perioperative complications: the cost of rescue. *JAMA Surg*. 2016;151:e163340.
47. Sheikh L, Croft R, Harmston C. Counting the costs of complications in colorectal surgery. *N Z Med J*. 2019;1321497:32–36.
48. Vonlanthen R, Slankamenac K, Breitenstein S, et al. The impact of complications on costs of major surgical procedures: a cost analysis of 1200 patients. *Ann Surg*. 2011;254:907–913.
49. Zogg CK, Ottesen TD, Kebaish KJ, et al. The cost of complications following major resection of malignant neoplasia. *J Gastrointest Surg*. 2018;22:1976–1986.
50. Woodfield J, Deo P, Davidson A, et al. Patient reporting of complications after surgery: what impact does documenting postoperative problems from the perspective of the patient using telephone interview and postal questionnaires have on the identification of complications after surgery? *BMJ Open*. 2019;9:e028561.
51. Porpiglia F, Morra I, Lucci Chiarissi M, et al. Randomised controlled trial comparing laparoscopic and robot-assisted radical prostatectomy. *Eur Urol*. 2013;63:606–614.
52. OECD. Length of hospital stay (indicator). Accessed March 17, 2020. https://data.oecd.org/healthcare/length-of-hospital-stay.htm

53. Regenbogen SE, Cain-Nielsen AH, Norton EC, et al. Costs and consequences of early hospital discharge after major inpatient surgery in older adults. *JAMA Surg*. 2017;152:e170123.
54. Health Forum L. *AHA Hospital Statistics 2020 ed*. 1st edn. American Hospital Association; 2020.
55. KFF. Hospital Inpatient Day Expenses. 2020. Accessed March 11, 2020. https://www.kff.org/state-category/health-costs-budgets/hospital-inpatient-day-expenses/
56. Merkow RP, Ju MH, Chung JW, et al. Underlying reasons associated with hospital readmission following surgery in the United States. *JAMA*. 2015;313:483–495.
57. Yu P, Chang DC, Osen HB, et al. NSQIP reveals significant incidence of death following discharge. *J Surg Res*. 2011;170:e217–e224.
58. Stitzenberg KB, Chang Y, Smith AB, et al. Exploring the burden of inpatient readmissions after major cancer surgery. *J Clin Oncol*. 2015;33:455–464.
59. Pisani MA, Albuquerque A, Marcantonio ER, et al. Association between hospital readmission and acute and sustained delays in functional recovery during 18 months after elective surgery: the successful aging after elective surgery study. *J Am Geriatr Soc*. 2017;65:51–58.
60. Esterhuizen TM, Thabane L. Con: meta-analysis: some key limitations and potential solutions. *Nephrol Dial Transplant*. 2016;31:882–885.
61. Tignanelli CJ, Napolitano LM. The fragility index in randomized clinical trials as a means of optimizing patient care. *JAMA Surg*. 2019;154:74–79.
62. Erskine J, Abrishami P, Charter R, et al. Best practice considerations on the assessment of robotic-assisted surgical systems: results from an international consensus expert panel. *Int J Technol Assess Health Care*. 2023;39:e39.
63. Marchegiani F, Siragusa L, Zadoroznyj A, et al. New robotic platforms in general surgery: what's the current clinical scenario? *Medicina (Kaunas)*. 2023;59:1264.

