Title: Volume-Outcome Relationship in Intra-abdominal Robotic-Assisted surgery. A Systematic Review

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Abstract
As robotic assisted surgery (RAS) expands to smaller centres, platforms are shared between specialities. Healthcare providers must consider case volume and mix required to maintain quality and cost-effectiveness. This can be informed, in-part, by the volume-outcome relationship. We perform a systematic review to describe the volume-outcome relationship in intra-abdominal robotic assisted surgery to report on suggested minimum volumes standards. A literature search of Medline, NICE Evidence Search, Health Technology Assessment Database and Cochrane Library using the terms: "robot*", "surgery", "volume" and "outcome" was performed. The included procedures were gynecological: hysterectomy, urological: partial and radical nephrectomy, cystectomy, prostatectomy, and general surgical: colectomy, esophagectomy. Hospital and surgeon volume measures and all reported outcomes were analysed. 41 studies, including 983149 procedures, met the inclusion criteria. Study quality was assessed using the Newcastle-Ottawa Quality Assessment Scale and the retrieved data was synthesised in a narrative review. Significant volume-outcome relationships were described in relation to key outcome measures, including operative time, complications, positive margins, lymph node yield and cost. Annual surgeon and hospital volume thresholds were described. We concluded that in centres with an annual volume of fewer than 10 cases of a given procedure, having multiple surgeons performing these procedures led to worse outcomes and, therefore, opportunities should be sought to perform other complimentary robotic procedures or undertake joint cases.

Key Words: volume, outcome, robotic assisted surgery

Statements and Declarations:
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Introduction

Robotic-assisted surgery (RAS) has seen a rapid growth globally in recent years and the breadth of procedures utilising the approach is increasing with multiple surgical specialities now employing robotic surgery for a variety of procedures for benign and malignant disease. This widespread expansion of RAS means robotic platforms are no longer exclusively available to large teaching hospitals or tertiary referral centres with high case volumes and this leads healthcare providers and planners to consider the case volume and mix required by smaller centres to ensure high quality and cost effectiveness [1,2].

In general, there is evidence indicating that surgical outcomes and cost effectiveness improve with increased procedure volume, whether for a particular hospital or individual surgeon [3-6]. The volume-outcome relationship has a number of contributory factors and their relative contribution is varied and debated as is the strength of the overall relationship [7]. It is possible that the early introduction of individual robotic platforms in a geographical area may result in the re-distribution of surgical volume towards a group of surgeons or an institution. Consequently, it is not clear if the reported benefits of RAS relate, in some part, to this volume-outcome relationship.

The volume-outcome relationship is the premise for minimal volume standards that are set for specific procedures worldwide including the Volume Pledge (USA) [8,9], Scottish Quality Performance Indicators/Getting it Right First Time (UK) [10,11], and Minimum volume regulations (Germany) [12]. These thresholds are informed, at least in part, by evidence of the volume-outcome relationship for each procedure. Surgeons, their health care networks and regulatory bodies, therefore, require information on the volume-outcome relationship in robotic surgery to consider how best to utilise platforms, especially in lower volume settings [13,14]. In addition, patients may wish to access this information to make an informed choice.

To date, research has been focussed on robotic equivalence, superiority and cost effectiveness compared to other minimally invasive or open approaches. The relationship between volume and outcome has not been addressed comprehensively across specialities utilising robotic platforms [15]. Institutions rolling out de-novo robotic programs must develop plans for surgeon training and access to robotic surgery. In the implementation phase, procedure volume and regular access is considered important in order to enable individuals to successfully ascend the learning curve. Beyond this point, little is known with regards to minimum procedure numbers to maintain RAS skills or what might constitute an optimum number of surgeons per system with regular RAS access to deliver a successful programme. We Therefore, we sought to review the literature to determine the volume-outcome relationship in robotic assisted intra-abdominal surgery. We conducted a systematic literature review of intra-abdominal robotic procedures performed in general surgery, gynecology and urology. Our aim was to report on whether institutional and surgeon specific volume outcome relationships exist for RAS in these surgical subspecialities and if so, report on suggested minimum surgical volumes to maintain high quality outcomes.

Materials and Methods

Search Strategy

A systematic literature search was performed using the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) statement (2020) and registered with the PROSPERO Registry [16,17]. The search used Medline, NICE Evidence Search, Health Technology Assessment Database and Cochrane Library to identify articles cited to and including the 31st October 2021. There was no start date, all records were considered. The terms used were: robot*, surgery, volume and outcome. There were no language criteria.

Study Selection

Studies were included if they related to intra-abdominal robotic surgery and measured the relationship between surgeon and/or hospital volume and any peri-operative outcome, including cost. Esophagectomy was included in the study, but the authors acknowledge that some approaches to this procedure are transthoracic.

Studies were excluded if they related to the learning curve, that is, they assessed outcomes from consecutive cases series or related to total number of cases a surgeon had performed (a surgeon's experience). Learning curve studies were excluded as these pertain more to the evidence base required for developing robotic training curricula rather than service design. Systematic reviews, editorial comments and letters to the editor were also excluded.

Data Extraction

The identified abstracts were screened to assess if they met the inclusion criteria. 10% of the identified abstracts were independently screened by two authors (ED,NG) and this process demonstrated 100% concordance in selection of articles for inclusion.

Full-text articles were then assessed for eligibility and the data was extracted for each study and included study design, year, country, procedure type and number, cut-off values for hospital or surgeon volume and the outcomes measured. The outcomes measured were grouped into intra-operative complications, including conversion to open, post-operative complications, including length of stay, oncological outcomes (positive margins/lymph node yield) and cost.

Quality Assessment

The Newcastle-Ottawa Quality Assessment Scale (NOS) was used to assess the quality of the included studies. The tool assesses the quality of nonrandomised studies and uses a star system which judges the studies on three areas: selection, comparability and outcome [18]. The criteria used and further explanation is available in Supplementary Material.

Results

The literature search identified 2956 potentially relevant records. Figure 1 illustrates how these were screened to identify 41 studies that met the inclusion criteria. The included studies are summarized in Tables 1-5.

Three specialties were included: General Surgery (4 studies), gynecology (6 studies) and Urology (31studies). 20 studies addressed surgeon volume and 33 studies addressed hospital volume. There were no prospective randomized controlled trials identified; studies included were retrospective observational studies.

The quality assessment of the included studies is available in Table 6. In general, most studies were of good quality, with 30 studies scoring 7 stars or more on the Newcastle-Ottawa Quality Assessment Scale. Where scores were lower, studies were scored down in the selection category for using a limited participation database or failure to include comment on data completeness and for failing to control for confounding factors in the outcome category. Confounding factors included patient demographics, co-morbidities, and disease parameters.

The results of the included studies are described below by specialty and then by the outcome measured (peri-operative complications, oncological outcomes and cost). The peri-operative complications measured in the included studies encompassed intra-operative events, such as conversion to open, organ injury and operative time; post-operative events, such as prolonged length of stay and re-admission; and functional outcomes, such as urinary continence and erectile dysfunction. The oncological outcomes measured in the included studies included positive margins, lymph node yield, disease recurrence and overall survival. All studies addressing cost originated from the United States and included colorectal procedures, radical prostatectomy and partial nephrectomy.

Gynecology (Table 1)
Five studies of hysterectomy and one study combining all robotic gynecology procedures were included; these studies demonstrated mixed results [19-24].

Three studies addressed surgeon volume. Ruiz et al compared surgeons performing one hysterectomy annually to those that performed more than one and found no significant relationship with peri-operative outcomes [21]. Brunes et al did find a significant relationship between surgeon volume and peri-operative outcomes, including blood loss and operative time [24]. Unger et al pooled all robotic gynecological procedures in their analysis and demonstrated that higher surgeon volume was associated with reduced rates of conversion to an alternative procedure [20].

Two further studies addressed hospital volume. Baba et al [22] demonstrated improved peri-operative outcomes with higher volumes using a threshold of ≥26cases/4years and Matsuo et al [23], using volume as a continuous variable, described the inverse relationship with higher volumes being associated with worse outcomes. Matsuo et al scored higher on the quality assessment, but it was noted that robotic assistance was more common in small bed capacity, non-urban centers and felt this may have confounded the results [23].

Cost was addressed in one study. Wright et al demonstrated a significant relationship for both surgeon and hospital volume with cost [19]. The relationship was seen to a greater degree in surgeon volume and cases performed for endometrial cancer by surgeons performing more than 50 procedures a year reduced the cost by $578 compared to those performing 5-15 cases/year.

There was no assessment of any oncological outcome in gynecological procedures.

General Surgery (Table 2)
Four general surgical studies were included, three colorectal and one esophagectomy. They demonstrated higher hospital and surgeon volumes were associated with fewer peri-operative complications [25-28].

For the colorectal procedures, the surgeon volume thresholds used were varied: >5cases/18months [25] and >30cases/year [26], but both studies had limited adjustment for confounding factors. The hospital volume thresholds used were more similar: >10 cases/18 months [25] and >12 cases/ year [27].

Although a single report, the esophagectomy study scored highly in the quality assessment. Hue et al used a hospital volume threshold of >9 esophagectomies /6 years to demonstrate a significant relationship with peri-operative complications [28].

With relation to oncological outcomes, increased lymph node yield was associated with increasing hospital volume in proctectomy and esophagectomy and lower positive margin in proctectomy, but not esophagectomy [27,28]. Overall survival was investigated in proctectomy and demonstrated hospitals performing >12 proctectomies /year, compared to hospitals performing >1–4 proctectomies /year, had higher overall survival (HR 1.4, 95% CI 1.1–1.9) [27].

Higher surgeon and hospital volumes were associated with lower costs in the colorectal procedures [25,26]. In both studies the cost difference between high and low surgeon volume was over $8000 per patient.

Urology

<u>Nephrectomy and Partial Nephrectomy</u> (Table 3)

Nine studies were included that addressed radical and partial nephrectomy [29-37].

A single study, addressing peri-operative complications in radical nephrectomy, found no significant relationship with surgeon volume, but included a small number of cases (n=573) [36].

Three studies reporting on surgeon volume in partial nephrectomy demonstrated a significant relationship with higher volume and more favorable outcomes [30-32]. The comparison in all three studies was between the highest volume groups (>11, >13 and >30 cases/year) and the lowest volume groups (1, 1-2, <7 cases/year), respectively.

Of six studies addressing hospital volume, five showed higher annual volumes were associated with more favorable outcomes [29,30,33-35]. Arora et al analyzed volume as a continuous variable and demonstrated the volume-outcome effect plateau at 18-20 cases/year [33]. The thresholds used in the other studies ranged from 20-71 cases/year [29,30,32,34,35].

With regards to oncological outcomes, lower positive margins rates were associated with higher volume in two [32,34] out of three studies assessing this variable [32,34,37]. Cost was assessed in two studies. Monn et al [29] showed no association with hospital volume and Khandwala et al [31] demonstrated reduced costs associated with increased surgeon volume, however, this finding was not significant when hospital clustering was considered.

<u>Radical Cystectomy</u> (Table 4)

Five studies assessed radical cystectomy [36,38-41], with two reporting on perioperative outcomes. Gray et al showed surgeon volume was associated with a shorter length of stay, but no difference in post-operative complications, using a threshold of 20 cases/year [36]. Hussein et al showed that cystectomies with ileal conduits performed by surgeons with a volume of more than 66 cases/year had a 55 min shorter procedure, but no relationship with hospital volume was demonstrated [39]. A later paper, Hussein et al demonstrated that operative time decreased as hospital volume increased and used volume as a continuous variable showing that procedure time was 1 min shorter per 1 procedure increase in volume [41].

In terms of oncological outcomes, increased lymph node yield [38,40] and lower rates of positive margins [40] were associated with increasing hospital volume.

Cost was not assessed in any of the five studies.

Radical Prostatectomy (Table 5)

Eighteen studies assessed radical prostatectomy [42-59]. The association between peri-operative complications and surgeon volume was addressed in four studies [44,46,55,58]. Two focused on the functional outcomes of urinary continence [44,55] and erectile dysfunction [55]. Urinary continence was the only outcome to hold significance, but this was only on univariate analysis in one study [44].

With regards to hospital volume, a significant association was seen with increasing volume and better perioperative outcomes in six of the nine studies assessing these outcomes [42,45,48,49,51,52,56,58,59]. In those studies demonstrating significance, the annual thresholds varied from 30 cases/year [42] to 145 cases/year [45].

Gershman et al modelling increasing hospital volume as a nonlinear continuous variable showed it was independently associated with improved rates of perioperative complications up to approximately 100 cases/year, beyond which there appeared to be marginal improvement [52].Higher hospital and surgeon volumes were associated with shorter operative times [46,53,58].

With regards to oncological outcomes, positive margins rates were assessed in four studies. For hospital volume, Sooriakumaran et al [47] and Godtman et al [58] showed no relationship, while Xia et al [56] and Chang et al [57] demonstrated an association with higher volume and lower rates using an annual threshold of 45 and 100 cases respectively. For surgeon volume, Godtman et al showed an association when comparing surgeons performing >75 cases/year to those performing <13cases/year [58].

Disease recurrence was assessed in two studies. Chang et al showed an associated with higher hospital volume and lower biochemical failure rates using a threshold of >100 cases/year [57]. Nyberg et al demonstrated that surgeon volume accounted for 19% of the heterogeneity in disease recurrence (both biochemical recurrence and residual disease), but did not adjust for confounding factors [55].

Cost was addressed six studies and found to have a significant association with volume in all [42,43,45,50,52,54]. Two studies addressed the association with both surgeon and hospital volume. Cole et al [50] found that nearly a third of the variation in robot-assisted radical prostatectomy cost was attributable to hospital characteristics, whereas, in contrast, Hyams et al [43] demonstrated an association with lower cost and higher surgeon, but not hospital volume. However, the latter study [43] used a smaller number of cases from a single state and used cases from earlier in the adoption of robotic surgery.

Discussion

Over the last four decades, the relationship between quantity and quality in surgery has been demonstrated [3,4]. Therefore, it is not unsurprising that the studies identified in this review have demonstrated a number of volume-outcome relationships in robotic assisted procedures. However, it is not possible to collate the evidence through a meta-analysis as the included studies use over-lapping patient cohorts and volume is categorised using different thresholds (e.g. in tertiles, quintiles or as a continuous variable). It is therefore challenging to propose minimal volume standards to assist service design and patient choice.

Minimal volume standards need to consider the relative merit of the outcomes that are related to volume. This analysis focused on perioperative outcomes, oncological outcomes and costs and the volume relationship described for each varied. For example, Xia et al showed that higher annual volumes were required to improve oncological outcomes as a lower positive margin rate in radical prostatectomy was associated with a hospital volume over 72 cases/year compared to 45 cases/year for lower rates of perioperative complications [56].

Also, to further confound the derivation of standards, surgeon volume could be considered cumulatively across related procedures. Hayn et al showed operative time and blood loss was reduced when surgeons performing robotic-assisted radical cystectomy also had robotic-assisted prostatectomy experience [60]. Unger et al's analysis considered this variable and pooled a surgeon's volume from all gynecology procedures in their analysis [20]. This is an important consideration when defining minimum volume standards as, in some regions, a given surgeon may perform multiple different procedures or operate in different geographical sites using the same robotic platform.

In addition, volume-outcome findings, and hence any derived minimal volume standards, may not be generalizable from one healthcare system to another. Outcomes relating to the delivery of care such as length of stay and cost, are likely to be highly dependent on the local context but also clinical management, such as transfusion practices [61,62]. A high proportion of the identified literature relates to data gathered in the United States and all studies addressing cost originated from the United States and, therefore, results may not be generalizable.

The authors have summarized the significant annual case volume thresholds identified for clinical outcomes in the included studies (Table 7). The ranges described could be used to guide recommendations for minimal volume stands, but are limited by the data available, with a notable paucity of data for the specialties other than urology, and the caveats we have discussed.

With regards to the cost effectiveness, ten of the 11 reports addressing this found a significant relationship. However, it may be more important to consider the cost effectiveness of the robotic platform as a whole, rather than by procedure. Feldstein et al describes instrument variation leading to increased costs as well as a scheduling threshold of 250-325 total annual cases for a single robotic platform despite a theoretical capacity of 780 cases/year [63]. Over this threshold, access to a platform may become challenging and limit productivity. This approach to assessing the volume outcome highlights the importance of standardisation, oversight and co-ordination within a robotic programme.

The main limitation of this review is the absence of a meta-analysis of the collated studies This is due to the variation in the threshold used and outcome definitions. It is important that future studies should consider how their data may be collated with other sources and/or more widely applied. The approaches using volume as a continuous variable and looking for a plateau in the volume-outcome relationship may be most useful.

Another limitation is that 20 (49%) of the studies included use data from more than 10 years ago. The volume-outcome relationship is likely to weaken as a procedure becomes more established and outcomes improve in general over time [64,65]. This is in part due to the adherence to an evidence based surgical technique and peri-operative care that is the result of iterative quality improvement [66]. Therefore, irrespective of the utility of minimal volume standards, there is a role in every setting for an outcomes-based quality improvement programme.

In general, for intra-abdominal robotic assisted surgery, high volumes are associated with better outcomes and increased cost effectiveness. It is reasonable to recommend trained robotic surgeons should maintain regular access to robotic cases, and seek, where possible, to optimise their volume. In centres with an annual volume of fewer than 10 cases of a given procedure, having multiple surgeons performing these procedures is not desirable and where it is necessary, opportunities should be sought to perform other complimentary robotic procedures or undertake joint cases.

As robotic platforms become more widely available, volume linked outcomes are balanced with equity of access, especially across less densely populated areas. Defining evidence based minimal volume standards will be helpful to inform this balance but, as we have described, it is challenging. Going forward, it will be important to create opportunities for collaborative data collection with unified volume and outcomes measures to assure and improve quality in robotic assisted surgery.

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Figure 1. PRISMA Flow Diagram.

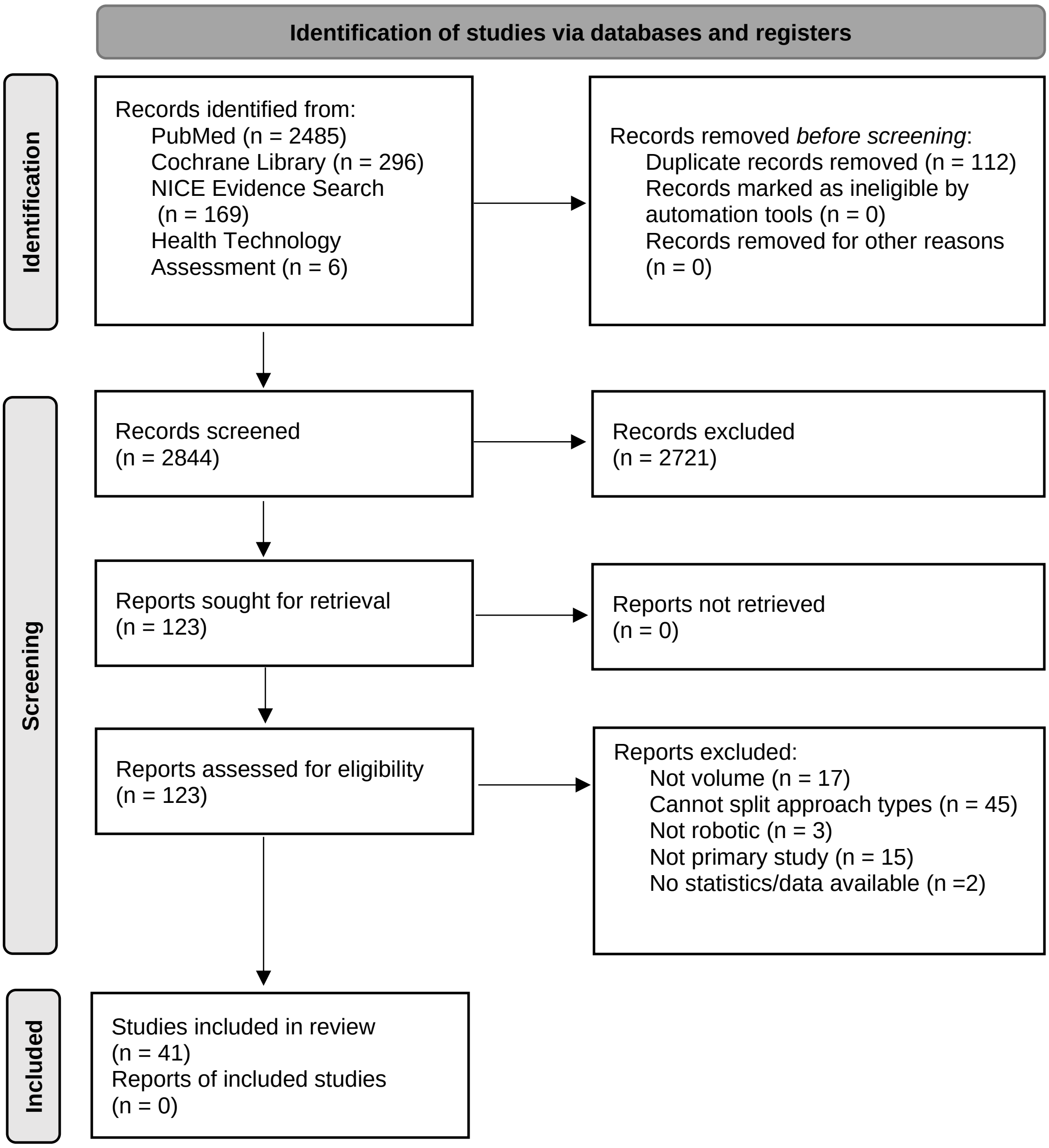

Fig 1. The PRISMA 2020 flow diagram for the identification and screening of the studies included in this systematic review.

Table 1. Gynecology

Study	Number of Procedures	Number of Hospitals	Number of Surgeons	Volume Type and Thresholds (time period)	Significant Findings	No significance
Wright et al, 2014 (19) USA	57994 Hysterectomy	>500	-	**Hospital and Surgeon** Continuous (per year)	**Hospital and Surgeon Volume** higher volume was associated with reduced cost	-
Unger et al, 2016 (20) USA	942 All Gynecological	1	-	**Surgeon** Very Low <3, Low 3-5, Medium 6-8, High 9-11 (per month)	higher volume was associated with lower rates of conversion to another procedure	
Ruiz et al, 2019 (21) USA	14057 Hysterectomy	-	245	**Surgeon** low 1, high ≥ 2 (per year)	-	intra-operative and post-operative complications
Baba et al, 2019 (22) Japan	200 Hysterectomy	24	-	**Hospital** low <10, intermediate 10-25, high ≥26 (per 4 years)	compared to intermediate volume, high volume was associated with shorter length of stay and operative time	intra-operative and post-operative complications
Matsuo et al, 2020 (23) USA	1175 Hysterectomy	163	-	**Hospital** Continuous (per 4 years)	higher volume was associated with higher rates of complications	higher volume was associated with *higher rate* post-operative complications
Brunes et al, 2021 (24) Sweden	1784 Hysterectomy	-	-	**Surgeon** - (per year)	higher volumes were associated with lower intra and post-operative complications and shorter operation time	

Tables 1-5 summarise the 41 studies included in this systematic review. In relation to outcome measures, operative time and conversion from robotic to open surgery is recorded distinctly from other intraoperative complications as it is the sole intra-operative outcome measured in a number of studies. The significant findings described were found on a multivariate statistical analysis and where this was not performed or a relationship was only significant on univariate analysis this is indicated specifically.

Table 2. General Surgery

Study	Number of Procedures (procedure type)	Number of Hospitals	Number of Surgeons	Volume Type and Thresholds (time period)	Significant Findings	No significance
Keller et al, 2013 (25) USA	1428 Colorectal	123	411	**Hospital** low <11, intermediate 11-20, high ≥21 **Surgeon** low <6, intermediate 6-15, high ≥16 (per 18 months)	**Hospital and Surgeon Volume** low volume was associated with higher rates of overall complications, longer length of stay and higher costs per episode of care	-
Bastawrous et al, 2018 (26) USA	957 Colorectal	32	-	**Surgeon** low <30, high ≥31 (per year)	compared to low volume, high volume was associated with shorter length of stay, lower conversion rate, and lower total hospital cost	post- operative complications
Concors et al, 2020 (27) USA	8107 Proctectectomy	-	-	**Hospital** low 1, intermediate 2-4, high 5-12, very high ≥13 (per year)	compared to very high volume, lower volume groups were associated with higher rates of conversion to open, positive margins, inadequate lymph node harvest and for very low and low groups, lower overall survival	readmission
Hue et al, 2020 (28) USA	1565 Oesophagectomy	212	-	**Hospital** low <10, high ≥10 (per 6 years)	compared to high volume, low volume was associated with lower number of lymph nodes, overall survival and longer length of stay	positive margins

Tables 1-5 summarise the 41 studies included in this systematic review. In relation to outcome measures, operative time and conversion from robotic to open surgery is recorded distinctly from other intraoperative complications as it is the sole intra-operative outcome measured in a number of studies. The significant findings described were found on a multivariate statistical analysis and where this was not performed or a relationship was only significant on univariate analysis this is indicated specifically.

Table 3. Radical and Partial Nephrectomy

Study	Number of Procedures	Number of Hospitals	Number of Surgeons	Volume Type and Thresholds (time period)	Significant Findings	No significance
Monn et al, 2014 (29) USA	17583 (Partial)	323	-	**Hospital** low 4-14, intermediate 14-40, high ≥35 (per year)	compared to low volume, high volume was associated with lower rates of post-operative complications	cost
Khandwala et al, 2017 (30) USA	33073 (Partial)	374	-	**Hospital** very low <6, intermediate 6-33, very high ≥34 **Surgeon** very low 1, Intermediate 2-11, very high ≥12 (per year)	**Hospital Volume** compared to very low, very high volume was associated with lower rates of conversion to radical nephrectomy (univariate analysis only) **Surgeon Volume** compared to very low volume, very high volume was associated with lower rates of conversion to radical nephrectomy	-
Khandwala et al, 2017 (31) USA	39773 (Partial)	-	-	**Surgeon** very low 1-2, low 3-4, intermediate 5-7, high 8-13, very high ≥14 (per year)	Compared to very low volume, very high volume was associated with lower rates of any complications, operative time, length of stay and cost	-
Peyronnet et al, 2018 (32) France	1222 (Partial)	11	-	**Hospital** low <20, moderate 20-44, high 45-70, very high ≥71 **Surgeon** low <7, intermediate 7-14, high 15-30, very high ≥31 (per year)	**Hospital Volume** compared to low volume, very high volume was associated with higher rated of attainment of the trifecta of no complications, warm ischaemia <25min, and negative margins **Surgeon Volume** compared to low volume, very high volume was associated with higher rates of attainment of the trifecta of no complications, warm ischaemia <25min, and negative margins	**Hospital and Surgeon Volume** all complications
Arora et al, 2018 (33) USA	2187 (Partial)	-	-	**Hospital** Continuous (per year)	odds of complications decreased with increasing volume, plateauing at 18-20 cases annually	-
Xia et al, 2018 (34)	18724	-	-	**Hospital**	compared to very low, higher volumes were	

USA	(Partial)			very low 3-45, low 46-72, medium 73-113, high 114-218, very high ≥219 (per year)	associated with lower rates of conversion, prolonged length of stay and positive margins	
Khene et al, 2019 (35) France	1342 (Partial)	7	-	**Hospital** low <20, intermediate 20-44, high 45-70, very high ≥71 (per year)	compared to low, higher volumes were associated with lower rates of complications	
Gray et al, 2020 (36) UK	573 (Radical)	-	-	**Surgeon** low <20, high ≥20 (per year)	no significant association with complications	post-operative complications and length of stay
Mellouki et al, 2021 (37) France	1359 (Partial)	9	-	**Hospital** Continuous **Surgeon** Low <15, moderate 15-30, high >30 (per year)	-	positive margins

Tables 1-5 summarise the 41 studies included in this systematic review. In relation to outcome measures, operative time and conversion from robotic to open surgery is recorded distinctly from other intraoperative complications as it is the sole intra-operative outcome measured in a number of studies. The significant findings described were found on a multivariate statistical analysis and where this was not performed or a relationship was only significant on univariate analysis this is indicated specifically.

Table 4. Cystectomy

Study	Number of Procedures	Number of Hospitals	Number of Surgeons	Volume Type and Thresholds (time period)	Significant Findings	No significance
Marshall et al, 2013 (38) Multiple countries	765	17	43	**Hospital** low <101, high ≥101 **Surgeon** low 1–10, intermediate 11–50, high ≥51 (per 7 years)	**Hospital Volume** compared to low volume, high volume was associated with higher rates of extended lymph node dissection **Surgeon Volume** compared to low volume, intermediate and high volume were associated with higher rates of extended lymph node dissection (univariate analysis only)	-
Hussein et al 2017 (39) Multiple countries	2134	27	-	**Hospital** **-** **Surgeon** Varied (High: >41-66 per year)	**Surgeon Volume** Operative time	**Hospital Volume** Operative time
Gray et al, 2020 (36) UK	1823	-	-	**Surgeon** low <20, high ≥20 (per year)	compared to low volume, high volume was associated with shorter length of stay	post-operative complications
Miguel et al, 2020 (40) USA	3687	-	-	**Hospital** very low 1–2, low 3–4, intermediate 5–9, high 10-19, very high ≥ 20 (per year)	increasing volume was associated with increased lymph node yield and decreased positive margin rate	-
Hussein et al, 2020 (41) Multiple countries	972	28	-	**Hospital** Continuous (per year)	procedure time was 1 min shorter per 1 procedure increase in volume	-

Tables 1-5 summarise the 41 studies included in this systematic review. In relation to outcome measures, operative time and conversion from robotic to open surgery is recorded distinctly from other intraoperative complications as it is the sole intra-operative outcome measured in a number of studies. The significant findings described were found on a multivariate statistical analysis and where this was not performed or a relationship was only significant on univariate analysis this is indicated specifically.

Table 5. Prostatectomy

Study	Number of Procedures	Number of Hospitals	Number of Surgeons	Volume Type and Thresholds (time period)	Significant Findings	No significance
Yu et al, 2012 (42) USA	2348	-	-	**Hospital** low 1-15, intermediate 16-29, high 30-54, very high 55-166 (per year)	high and very high volume hospitals associated with fewer complications low volume hospitals associated with longer mean length of stay higher volume hospitals associated with lower cost	-
Hyams et al, 2013 (43) USA	1499	51	-	**Hospital** low <61, high ≥61 **Surgeon** low <40, high ≥40 (per year)	**Hospital and Surgeon Volume** compared to low volume, high volume was associated with lower costs	-
Sammon et al, 2013 (44) USA	1270	1	5	**Surgeon** - (per 2years)	higher volume associated with higher rates of immediate urinary continence (univariate analysis only)	-
Sammon et al, 2013 (45) USA	46562	-	-	**Hospital** low 1-74, intermediate 75-137, high 145-279, very high 333-869 (per year)	compared to low volume, high and very high volume was associated with fewer post-operative complications, prolonged length of stay and lower costs	intra-operative complications
Carter et al, 2014 (46) USA	3458	-	-	**Hospital** Quartiles (per year) **Surgeon** Quartiles (per 5years)	**Hospital and Surgeon Volume** compared to the lowest quartile, the higher volumes were associated with shorter operative time	-
Sooriakumaran et al, 2014 (47) Multiple countries	7697	8	-	**Hospital** Comparison to highest volume centre (2696) (per 11years)	-	positive margin
Friðriksson et al, 2014 (48) Sweden	6393	-	-	**Hospital** low <30, intermediate 30-149, high ≥150	-	post-operative complications

				(per year)		
Wiener et al, 2015 (49) USA	82338	-	-	**Hospital** Quartiles (per year)	compared to lowest quartile, higher volumes were associated with lower rates of conversion to open	-
Cole et al, 2016 (50) USA	291015	197	667	**Hospital** 90th percentile ≥760 **Surgeon** 90th percentile (≥386) (per year)	**Hospital and Surgeon Volume** volume over the 90th percentile was associated with lower costs	-
Hirasawa et al, 2017 (51) Japan	3214	44	148	**Hospital** low <100, high ≥100 (per year)	high volume was associated with lower rates of intra-operative complications high volume was associated with lower post-operative complications (on univariate analysis only)	-
Gershman et al, 2017 (52) USA	140671	2472	-	**Hospital** very low <13, low 13-30, intermediate 31-66, high 67-820 (per 2years)	compared to very low volume, high volume had lower rates of intra- and post- operative complications, prolonged length of stay and costs	-
Simon et al, 2017 (53) USA	614	6	-	**Hospital** Continuous (per year)	increasing volume was associated with decreasing operative time	
Mukherjee et al, 2019 (54) USA	52151	-	-	**Hospital** low <107, high ≥107 (per 5years)	increasing volume was associated with lower cost	-
Nyberg et al, 2020 (55) Sweden	4003	14	68	**Surgeon** - (per year)	volume accounted for 19% heterogeneity in disease recurrence	post-operative complications including urinary continence and erectile function
Xia et al, 2020 (56) USA	114957	617	-	**Hospital** very low 3-45, low 46-72, intermediate 73-113, high 114-218, very high ≥219 (per year)	compared to very low volume, higher volumes had lower rates of conversion, prolonged length of stay, re-admission and positive margin rates	mortality
Chang et al, 2021 (57) Taiwan	816	44	-	**Hospital** low <26 intermediate 26-50 high 51-100	very high volume compared to the other groups had lower biochemical-failure and positive margin rates	-

				very high >100 (per year)		
Godtman et al, 2021 Sweden (58)	9810		-	**Hospital** very low <50 low 50-100 intermediate 100-150 high 150-200 very high >200 **Surgeon** very low <13 low 13-25 intermediate 25-50 high 50-75 very high >75 (per year)	**Hospital Volume** Compared to very low, very high volumes had shorter operative times **Surgeon Volume** Compared to very low, very high volumes had shorter operative times, smaller blood loss, lower positive margins	**Hospital Volume** Blood loss, positive margins, readmission **Surgeon Volume** Re-admission
Lindenberg et al, 2021 Netherlands (59)	907	8	-	**Hospital** low 0-50 intermediate 50-100 high100-150 very high >150 (per year)	-	urinary continence and erectile function

Tables 1-5 summarise the 41 studies included in this systematic review. In relation to outcome measures, operative time and conversion from robotic to open surgery is recorded distinctly from other intraoperative complications as it is the sole intra-operative outcome measured in a number of studies. The significant findings described were found on a multivariate statistical analysis and where this was not performed or a relationship was only significant on univariate analysis this is indicated specifically.

Table 6 Newcastle - Ottawa Quality Assessment Scale for All Included Studies

Study	Selection (****)	Comparability (**)	Outcome (***)	Overall (*********)
Arora et al 2018	****	**	**	********
Baba et al 2019	***	-	*	****
Bastawrous et al 2018	***	-	**	*****
Brunes et al 2021	****	**	***	*********
Carter et al 2014	***	**	**	*******
Chang et al 2021	**	**	**	******
Cole et al 2016	***	**	**	*******
Concors et al 2019	****	**	**	********
Friõriksson et al 2014	****	**	***	*********
Gershman et al 2017	****	**	**	********
Godtman et al 2021	***	**	***	********
Gray et al 2020	****	**	**	********
Hirasawa et al 2017	**	*	*	****
Hue et al 2020	****	**	**	********
Hussein et al 2017	**	**	***	*******
Hussein et al 2020	**	**	**	******
Hyams et al 2013	****	*	***	********
Keller et al 2013	***	*	**	******
Khandwala et al 2017 (Urol Oncol)	***	**	***	********
Khandwala et al 2017 (J Endourol)	***	**	***	********
Khene et al 2019	***	**	**	*******
Lindenberg et al 2021	**	**	****	********
Marshall et al 2013	**	**	*	*****
Matsuo et al 2020	****	**	***	*********
Mellouki et al 2021	**	**	*	*****
Miguel et al 2020	****	*	**	*******
Monn et al 2014	***	**	**	*******
Mukerjee and Kamal 2019	****	**	***	*********
Nyberg et al 2020	**	-	***	*****
Peyronnet et al 2018	***	**	**	*******
Ruiz et al 2018	****	**	***	*********
Sammon et al 2013 (J Endourol)	**	**	***	*******
Sammon et al 2013 (J Urol)	***	-	**	*****
Simon et al 2017	**	**	***	*******
Sooriakumaran et al 2014	***	*	***	*******
Unger et al 2016	***	-	***	******
Weiner et al 2015	****	**	**	*******
Wright et al 2014	***	**	**	*******
Xia et al 2018	****	**	**	********
Xia et al 2020	****	**	***	*********
Yu et al 2012	***	**	**	*******

The Newcastle Ottawa Scale (NOS) scores for each of the included studies. The maximum score possible for each section is given in brackets in the heading row. Further details of scoring system and rationale for each study score can be found in Supplementary Material.

Table 7. The range of volume thresholds for significant improvement in all clinical outcomes

	Hospital Volume	Surgeon Volume
Hysterectomy	6.5 (1)	-
Colorectal	5-13 (2)	4-31 (2)
Oseophagectomy	1.7(1)	-
Nephrectomy	-	-
Partial Nephrectomy	20-71 (5)	12-31 (3)
Cystectomy	-	20 (1)
Prostatectomy	30-145 (6)	75 (1)

The thresholds are given in cases/per year and the total number of studies contributing to the range are included in brackets. Cost and operative time alone have been excluded as outcomes, all other outcomes have been included in the summary. Where no data was available '-' is entered.

Supplementary Material.

Volume-Outcome Relationship in Intra-abdominal Robotic-Assisted surgery. A Systematic Review
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Newcastle - Ottawa Quality Assessment Scale For Cohort Studies for All Included Studies

Study (Max Score)	**Procedure**	**Selection** (****)	**Comparabilit y (**)**	**Outcome (***)**	**Overall** (*********)	
Arora et al 2018 [33]	Partial Nephrectomy	****	**	**	********	S: All U C: Adju O: No s
Baba et al 2019 [22]	Hysterectomy	***	-	*	****	S: Limi C: No a O: Self comple
Bastawrous et al 2018 [26]	Colorectal	***	-	**	*****	S: Limi C: No a O: No s
Brunes et al 2021 [24]	Hysterectomy	****	**	***	*********	S: Limi registri C: Adju O: Mis
Carter et al 2014 [46]	Prostatectomy	***	**	**	*******	S: Limi C: Adju O: Mis
Chang et al 2021 [57]	Prostatectomy	**	**	**	******	S: Limi adjuvar C: Adju O: No s
Cole et al 2016 [50]	Prostatectomy	***	**	**	*******	S: Limi C: Adju O: No s
Concors et al 2019 [27]	Colorectal	****	**	**	********	S: Inclu C: Adju O: No s
Friðriksson et al 2014 [48]	Prostatectomy	****	**	***	*********	S: Inclu C: Adju O: Sam
Gershman et al 2017 [52]	Prostatectomy	****	**	**	********	S: Inclu C: Adju O: No s
Godtman et al 2021 [58]	Prostatectomy	***	**	***	********	S: Limi low vol C: Adju O: Mis
Gray et al 2020 [36]	Nephrectomy and Cystectomy	****	**	**	********	S: Inclu C: Adju O: No s
Hirasawa et al 2017 [51]	Prostatectomy	**	*	*	****	S: Limi C: Adju O: Self comple
Hue et al 2020 [28]	Oesophagectomy	****	**	**	********	S: Inclu C: Adju

						O: No s
Hussein et al 2017 [39]	Cystectomy	**	**	***	*******	S: Limi C: Adju O: Stat
Hussein et al 2020 [41]	Cystectomy	**	**	**	******	S: Limi C: Adju O: No s of exclu
Hyams et al 2013 [43]	Prostatectomy	****	*	***	********	S: Inclu C: Adju O: All
Keller et al 2013 [25]	Colorectal	***	*	**	******	S: Limi C: Adju O: No s
Khandwala et al 2017 [30]	Partial Nephrectomy	***	**	***	********	S: Limi C: Adju O: All
Khandwala et al 2017 [31]	Partial Nephrectomy	***	**	***	********	S: Limi C: Adju O: All
Khene et al 2019 [35]	Partial Nephrectomy	***	**	**	*******	S: Limi C: Adju O: No s
Lindenberg et al 2021 [59]	Prostatectomy	**	**	****	********	S: Limi C: Adju O: Pati for
Marshall et al 2013 [38]	Cystectomy	**	**	*	*****	S: Limi C: Adju O: Self comple
Matsuo et al 2020 [23]	Hysterectomy	****	**	***	*********	S: Inclu C: Adju O: Mis
Mellouki et al 2021 [37]	Partial Nephrectomy	**	**	*	*****	S: Limi C: Adju O: Self comple
Miguel et al 2020 [40]	Cystectomy	****	*	**	*******	S: Inclu C: Adju O: No s
Monn et al 2014 [29]	Partial Nephrectomy	***	**	**	*******	S: Limi C: Adju O: Stat
Mukherjee & Kamal 2019 [54]	Prostatectomy	****	**	***	*********	S: Inclu C: Adju O: Mis
Nyberg et al 2020 [55]	Prostatectomy	**	-	***	*****	S: Limi status u C: No a O: Mis
Peyronnet et al 2018 [32]	Partial Nephrectomy	***	**	**	*******	S: Repr C: Adju O: No s
Ruiz et al 2018 [21]	Hysterectomy	****	**	***	*********	S: Repr C: Adju O: Mis
Sammon et al 2013 [44]	Prostatectomy	**	**	***	*******	S: Sing C: Adju

						O: Mis
Sammon et al 2013 [45]	Prostatectomy	***	-	**	*****	S: Lim C: No a O: No s
Simon et al 2017 [53]	Prostatectomy	**	**	***	*******	S: Lim case le C: Adju O: Stat
Sooriakumaran et al 2014 [47]	Prostatectomy	***	*	***	*******	S: Lim study u C: Adju O: Mis
Unger et al 2016 [20]	All Gynaecology	***	-	***	******	S: All c C: Not O: Mis
Weiner et al 2015 [49]	Prostatectomy	****	**	**	*******	S: Inclu C: Adju O: No s
Wright et al 2014 [19]	Hysterectomy	***	**	**	*******	S: Lim admiss C: Adju O: No s
Xia et al 2018 [34]	Partial Nephrectomy	****	**	**	********	S: Inclu C: Adju O: No s
Xia et al 2020 [56]	Prostatectomy	****	**	***	*********	S: Inclu C: Adju O: Mis
Yu et al 2012 [42]	Prostatectomy	***	**	**	*******	S: Lim C: Adju O: Stat

Newcastle - Ottawa Quality Assessment Scale for Cohort Studies. Scoring Template.

A study can be awarded a maximum of one star for each numbered item within the Selection and Outcome categories.
A maximum of two stars can be given for Comparability.

Selection

1) Representativeness of the exposed cohort
   a) truly representative of the average **_>70%_** (describe) in the community ✵
   b) somewhat representative of the average **_>50%_** the community ✵
   c) selected group of users eg nurses, volunteers
   d) no description of the derivation of the cohort
2) Selection of the non exposed cohort
   a) drawn from the same community as the exposed cohort ✵
   b) drawn from a different source
   c) no description of the derivation of the non exposed cohort
3) Ascertainment of exposure
   a) secure record (eg surgical records) ✵
   b) structured interview ✵
   c) written self report
   d) no description
4) Demonstration that outcome of interest was not present at start of study
   a) yes ✵
   b) no

Comparability

1) Comparability of cohorts on the basis of the design or analysis
   a) study controls for **_demographic characteristics and comorbidity measurments_** (select the most important factor) ✵
   b) study controls for any additional factor ✵ **_demographic characteristics only _** (This criteria could be modified to indicate specific control for a second important factor.)

Outcome

1) Assessment of outcome
   a) independent blind assessment ✵
   b) record linkage ✵
   c) self report **(including surgeon report where not linked to record or validated as is NCDB)**
   d) no description
2) Was follow-up long enough for outcomes to occur
   a) yes (select an adequate follow up period for outcome of interest) ✵
   b) no
3) Adequacy of follow up of cohorts
   a) complete follow up - all subjects accounted for ✵
   b) subjects lost to follow up unlikely to introduce bias - small number lost - **less than 50%** follow up, or description provided of those lost) ✵
   c) follow up rate **more than 50**and no description of those lost
   d) no statement or unclear/partial relevance