Systematic Review

The learning curve of the robotic-assisted lobectomy—a systematic review and meta-analysis

Ashley R. Wilson-Smith[1,2,3,4#], Naomi Anning[4#], Benjamin Muston[2], Aditya Eranki[5], Michael L. Williams[2,6], Christian J. Wilson-Smith[7], Diego G. Rivas[8], Tristan D. Yan[1,2]

[1]The Chris O'Brien Lifehouse Center, Sydney, Australia; [2]The Collaborative Research Group (CORE), Sydney, Australia; [3]The Hunter Medical Research Institute (HMRI), Newcastle, Australia; [4]Department of Vascular Surgery, The John Hunter Hospital, Newcastle, Australia; [5]The St. George Hospital, Sydney, Australia; [6]Department of Cardiothoracic Surgery, Dunedin Public Hospital, Dunedin, New Zealand; [7]The University of New South Wales Medical School, Sydney, Australia; [8]Department of Thoracic Surgery and Minimally Invasive Thoracic Surgery Unit (UCTMI), Coruña University Hospital, A Coruña, Spain

[#]These authors contributed equally to this work.

Correspondence to: Dr. Ashley R. Wilson-Smith. The Collaborative Research Group (CORE), Sydney, Australia; Chris O'Brien Lifehouse, Sydney, Australia; The John Hunter Hospital, Newcastle, Australia. Email: wilsonsmithash597@gmail.com.

Background: Early studies have illustrated the robotic lobectomy to be safe, oncologically effective, and economically feasible as a therapeutic modality in the treatment of thoracic malignancies. The 'challenging' learning curve seemingly associated with the robotic approach, however, continues to be an often-cited factor to its ongoing uptake, with the overwhelming volume of these surgeries being performed in centers of excellence where extensive experience with minimal access surgery is the norm. An exact quantification of this learning curve challenge, however, has not been made, begging the question of whether this is an outdated assumption, versus fact. This systematic review and meta-analysis sort to clarify the learning curve for robotic-assisted lobectomy based on the existing literature.

Methods: An electronic search of four databases was performed to identify relevant studies outlining the learning curve of robotic lobectomy. The primary endpoint was a clear definition of operator learning (e.g., cumulative sum chart, linear regression, outcome-specific analysis, etc.) which could be subsequently aggregated or reported. Secondary endpoints of interest included post-operative outcomes and complication rates. A meta-analysis using a random effects model of proportions or means was applied, as appropriate.

Results: The search strategy identified twenty-two studies relevant for inclusion. A total of 3,246 patients (30% male) receiving robotic-assisted thoracic surgery (RATS) were identified. The mean age of the cohort was 65.3±5.0 years. Mean operative, console and dock time was 190.5±53.8, 125.8±33.9 and 10.2±4.0 minutes, respectively. Length of hospital stay was 6.1±4.6 days. Technical proficiency with the robotic-assisted lobectomy was achieved at a mean of 25.3±12.6 cases.

Conclusions: The robotic-assisted lobectomy has been illustrated to have a reasonable learning curve profile based on the existing literature. Current evidence on the oncologic efficacy and purported benefits of the robotic approach will be bolstered by the results of upcoming randomized trials, which will be critical in supporting RATS uptake.

Keywords: Robotic thoracic surgery; robotic lobectomy; learning curve

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Introduction

Since its mainstream inception in the early 2000s, robotic surgery has come to be well-established in most surgical subspecialties (1). Robotic-assisted thoracic surgery (RATS), specifically the robotic-assisted lobectomy, has proven itself to be safe, oncologically efficacious and economically cost-effective, offering patients the potential for improved cosmesis, shorter intensive care and hospital length-of-stays, with equivalent or better outcomes compared to traditional approaches (2). Encouraging short-term results have been reiterated in the preliminary outcomes of the Robotic-Assisted Versus Video-Assisted Thoracoscopic Lobectomy (RVlob) trial (3). The significant learning curve of robotic lobectomy, however, continues to be presented as a limiting factor to its ongoing uptake, with the overwhelming volume of these surgeries being performed in centers of excellence where strong experience in minimal access approaches (e.g., video-assisted thoracoscopic surgery) is the baseline. However, no exact, holistic quantification of the learning curve of this robotic approach has been made to date, begging the question as to whether this is an outdated assumption, versus fact. This systematic review sort to clarify the learning curve for robotic-assisted lobectomy based on the existing literature.

Methods

Literature search strategy

The methods for this systematic review adhered to the guidelines outlined by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) updated statement (4). Four electronic databases were used to perform the literature searches, encompassing EMBASE, Ovid MEDLINE, PubMed and SCOPUS. These databases were searched from the date of database inception through to 24th July 2022. For examination of the learning curve associated with robotic lobectomy, a search strategy using the combination of keywords and Medical Subject Headings (MeSH) including (robotic assisted OR robotic surgery OR robotic thoracic surgery OR RATS OR RAT OR RTS) AND (lobar resection OR lobectomy) AND (learning curve) was utilized (see Figure S1). Predefined selection criteria were applied to assess for inclusion. Each study was screened independently by two co-authors, with any conflicts resolved prior to progression. Where the title and/or abstract provided insufficient detail in the determination of relevance for additional screening, a full-text review of the record was carried out in the first instance. Reference lists of the included studies were reviewed at completion of the database search to identify any extra, relevant studies not already included.

Inclusion and exclusion criteria

Studies were included in the review if they examined the learning curve of their operators undertaking robotic lobectomy; specifically, reported perioperative outcomes across time. Studies were excluded for: (I) non-English reporting; (II) case reports/small case series with <10 subjects; (III) registries without recruiting details; (IV) no mention of operator learning curve.

Primary and secondary endpoints

The primary endpoint for analysis was operator learning curve results, where clear distinction of incremental or decremental outcomes across case-volume and time were reported (i.e., in distinct operating phases with an overall aggregated case volume, numeric patient clusters, cumulative sum charts, linear regression, etc.). Secondary endpoints of interest included mean console and dock time, blood loss, chest tube duration, length of hospital stay and total lymph nodes removed (with stations if available).

Data extraction, critical appraisal and quality assessment

Two independent reviewers extracted data directly from publication texts, tables and figures. A third reviewer independently reviewed and confirmed all extracted data. Differing opinions between the two main reviewers were resolved through discussion led by the primary investigator. Attempts were made to clarify insufficient/indistinct data from authors of included studies, as required. Data was extracted in a way that each study was effectively treated as a case series, irrespective of underlying design. Outcomes of interest that were not reported (or were not reported sufficiently for meta-analysis) were namely: renal impairment, hypertension, diabetes, chronic obstructive pulmonary disease, atrial fibrillation, peripheral vascular disease, coronary artery disease, prior acute coronary syndrome or myocardial infarction, cerebrovascular accident or transient ischemic attack, reoperation and readmission (30-day). The Canadian Institute of Health Economics

Quality Appraisal score was used as the quality assessment tool (5). Studies were defined as low quality with scores <10/19, moderate quality with score 11–15/19 and high quality with scores >15/19 (see Table S1). Risk of bias was assessed using the "Risk of Bias in Non-randomized Studies of Interventions" (ROBINS-I) tool and is visually presented (see Figure S2) (6).

Statistics

A meta-analysis of proportions or means was performed for categorical and continuous variables, as appropriate, by an independent reviewer. A random effects model was used to account for differing regions, surgeon experience, surgical technique and equipment, and management protocols across the included studies. Means and standard deviations (SDs) were calculated from the median, where reported, using the methods described by Wan and colleagues (7). Pooled data and SD were presented as N (%) ± SD with 95% confidence intervals (CIs). For outcome data, heterogeneity amongst studies was assessed using the I^2 statistic. Thresholds for these values considered as low, moderate and high heterogeneity were 0–49%, 50–74% and greater than or equal to 75%, respectively. Meta-analysis of proportions or means was performed using Stata (version 17.0, StataCorp., Texas, USA). Survival data was calculated from the aggregation of Kaplan-Meier (KM) curves from the included studies, if reported, by utilizing the methods of Guyot and colleagues (8).

Results

Study characteristics

A total of 209 studies on the learning curve of robotic lobectomies were identified in the literature search, with twenty-two progressing to inclusion. The studies included in this review were overwhelmingly retrospective (9-28) versus prospective (29,30) in nature. The majority of studies (twelve) were drawn from North America, with the remainder from Europe (three), China (three), Japan (two) Korea (one) and the Middle East (one). Upon quality assessment, twelve studies were deemed to be of high quality (9,13,15-17,19-22,25,26,29), nine of medium quality (10,11,14,18,23,24,27,28,30) and one of low quality (12). Risk of bias assessment illustrated low-risk in the majority of studies, with only four demonstrating minor concerns (11,23,28,30) (see Figure S2).

Baseline demographic characteristics, operative details and post-operative outcomes

Baseline demographic characteristics and operative details are reported in *Table 1*. A total of 3,246 patients (30% male) receiving RATS were identified across an operative period of 2011 to 2020. Long-term follow-up data were poorly reported, and hence KM analysis was not carried out. The robotic-assisted lobectomies in this analysis were performed in the established complete port robotic lobectomy (CPRL) robotic-assisted lobectomy-4 (RAL-4) manner. The Da Vinci^R Surgical System (Intuitive Surgical Inc., Sunnyvale, California, USA) Xi or Si was the primary systems of choice. All studies reported port access sites, anesthetic delivery and ventilation methods. Variably, a combination of working ports, typically 2–3×8 mm and 1–2×12 mm utility ports were utilized, per institution and surgeon preference. The mean age of the cohort was 65.3±5.0 years. FEV_1 preoperatively was 2.5±0.2 L/s. Tumor size was 2.2±0.55 cm. Mean operative, console, and dock time was 190.5±53.8, 125.8±33.9, and 10.2±4.0 minutes, respectively. Blood loss was 90.0±85.4 mL. Chest tube duration was 3.5±0.8 days. Lymph node dissection was 14.7±5.0 nodes per case. Length of hospital stay was 6.1±4.6 days. Outcomes of interest including affected lobes, tumor histology and individual staging are reported in supplementary materials (available on request).

Learning curve outcomes

Learning curve outcomes were reported via cumulative sum chart (CUSUM) analysis with or without risk adjustment, non-CUSUM linear regression modelling or outcome-specific analysis. These values were aggregated using meta-analysis with a random effects model. Case volume for baseline proficiency was 25.3±12.6 cases. All included studies reported the primary endpoint initially sought. Sensitivity analysis of high-quality studies did not significantly alter the case volume required for proficiency, with 24.8±3.6 cases required. *Figure 1* details the reported learning curve volumes required for technical proficiency across the included studies.

Discussion

Robotic-assisted approaches in thoracic surgery are growing in popularity, all in an effort to offer patients equivalent or improved outcomes in comparison to more invasive,

Table 1 Baseline demographic characteristics and operative details

Variable of interest	Values identified	95% confidence interval
Cohort size (n)	3,246	–
Males (n)	972	–
Mean age of cohort (years), mean ± SD	65.3±5.0	63.8–66.8
Mean FEV_1 pre-op (L/s), mean ± SD	2.5±0.2	2.5–2.3
Mean tumor size (cm), mean ± SD	2.2±0.55	2.2–2.3
Mean operation time (min), mean ± SD	190.5±53.8	99.7–204.3
Mean console time (min), mean ± SD	125.8±33.9	58.3–155.5
Mean dock time (min), mean ± SD	10.2±4.0	10.7–13.6
Mean blood loss (mL), mean ± SD	90.0±85.4	28.6–111.3
Mean chest tube time (days), mean ± SD	3.5±0.8	2.5–4.0
Mean length of stay (days), mean ± SD	6.1±4.6	4.8–6.4
Mean lymph nodes removed (nodes), mean ± SD	14.7±5.0	12.3–16.8
Mean conversion to open procedure (n), mean ± SD	2.8±2.6	–
Mean learning curve (case number), mean ± SD	25.3±12.6	14–56

SD, standard deviation; FEV_1, forced expiratory volume in 1 second; pre-op, pre-operative.

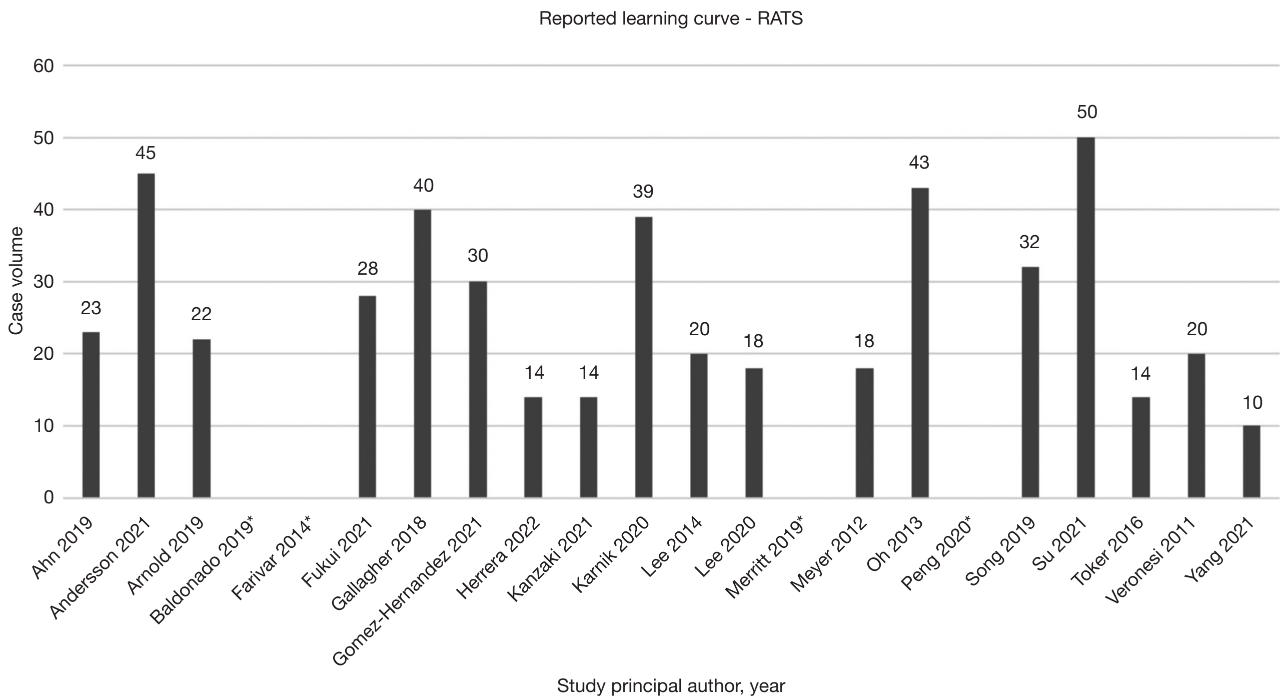

Figure 1 Reported learning curve data across studies. *, studies reported learning curve outcomes in 'phases' not amenable to statistical aggregation. RATS, robotic-assisted thoracic surgery.

traumatic techniques (1). However, due to the often-cited steep learning curve associated with these approaches and the higher initial costs, RATS remains localized to centers of excellence and largely limited to surgeons proficient with video-assisted thoracoscopic (VATS) approaches. Alongside this steep learning curve, it has also been questioned as to whether it represents a pragmatic modality when outcomes with VATS as a minimally invasive approach are excellent. The aim of this systematic review and meta-analysis was to provide the most up-to-date, comprehensive assessment of the literature examining the learning curve of robotic-assisted lobectomy. No systematic review or meta-analysis has previously been conducted on this subject, with only one recent review paper outlining coherent, summarized evidence to date (31).

Reporting of learning curve experience across included studies

Depending on the metric of interest and the degree of initial technical competency with VATS, the learning curve for robotic-assisted lobectomy was identified to be 25.3±12.6 cases. These values encompass acceptable case volumes for subjective surgeon comfort and ease with the robotic system, reflect the point of reduction of operative times towards the 'plateau' and 'mastery' phases of learning, and complication rates such as postoperative air leaks and transfusion amounts (10). Unsurprisingly, in those cohorts where surgeons were already considered experts in VATS (without additional quantification of degree of expertise), or when they were the sole robotic operators in an institution, technical proficiency was achieved earlier in the learning process (22,23,27). This is likely due to the operator familiarity with adjusting for heavily magnified views, ease of navigation around obstructions, repetition learning and a focus on minimizing bleeding given the disproportionate effect of small amounts of bleeding on visualization in both VATS and particularly in RATS. Accordingly, in these institutions, there did not appear to be any statistical difference in complication rates in those studies with comparison to VATS (14,25). RATS' safety profile does appear to be preserved even in those cohorts where operators do not have significant previous VATS experience (20).

It is difficult to parameterize an acceptable definition of what constitutes a 'learning curve', given the inherent variability of inter-operator experience, previous exposure to minimally invasive techniques, and that proctorship and institutional access to minimal access surgery were not elaborated upon or discussed within the literature, bar superficial comments on prior experience or mandatory clinical requirements. The papers included for analysis, indeed representing the most appropriate pool with relevant data on the learning curve of robotic lobectomies, are notably technical papers at their core; more relevant information for a surgical audience, such as the prior number of VATS cases done per surgeon, experience on earlier robotic platforms, proctorship and so on, are unfortunately not discussed in significant detail. Only three studies made specific, though limited, mention of proctorship (19,20,24), with two studies reporting mandatory proctorship cases required by their hospital's licensing board, and one study outlining a recommendation for proctorship after the initial learning phase.

With respect to the variability of case volumes, the highest case volume required to achieve technical competency was noted in the cohort described by Su *et al.* (10). This was largely attributed to the cases being performed by four separate surgeons with significant variability in experience, with the most senior surgeon having fifteen years of VATS experience, a mid-career surgeon with eight years of experience, and two immediate post-fellowship surgeons. None of the operators had any prior experience with robotic procedures. Of note, independent of this prior VATS experience, their case volumes required to achieve competency was consistent across all operators–a finding suggestive of a specific learning curve for RATS. The lowest case volume required to achieve technical competency was noted in Yang *et al.*'s cohort (29), with only ten cases suggested to overcome the learning curve. A strong suggestion was made, however, that mastery of the technique would not be achieved until far later with over fifty cases. Docking times were higher in some phases of their learning curve, where the attending surgeon docked the arms in the earlier phases with subsequent transition to the fellows in later phases. Additionally, their teams were also involved in other robotic procedures (i.e., mediastinal resections, esophagectomies), which would also have contributed to more rapid familiarity with the Da Vinci platform.

RATS versus VATS—a significant evolution?

One clear advantage of the robotic approach is the proposed increased clearance of node stations, overall nodal number dissected and reduced nodal upstaging compared to VATS, an important consideration in both early and more advanced cases (20,25,26). Merritt *et al.* reported a significant increase in total nodes harvested in their robotic cohort versus thoracoscopic patients with 14.21±6.45 versus 10.39±5.68 nodes removed, respectively (25), though other studies reporting this benefit were not able to meet statistical significance; Gallagher makes note that no difference between their VATS and RATS cohort with respect to nodal upstaging was found, however, suggesting that even in the early phases of RATS experience, it can replicate the resection completeness of other approaches even if total nodes removed were not greater in comparison (20). Whether these data are preserved when accounting for operator skill level has yet to be determined given the lack of operator skill data. It is also difficult to ascertain whether the robotic lobectomy confers a benefit in terms of ICU and hospital length of stay in comparison to experienced VATS operators, with some studies reporting no difference between the two approaches (23). The upcoming RVlob randomized control trial will hopefully elucidate the oncologic efficacy and course of recovery in these patients past the short-term (3).

Limitations

There are a number of limitations that need to be considered when examining the results of this review. The principal concern is that the generalizability of the results to those with little training in minimally invasive approaches is limited; surgeons with baseline to minimal levels of competency with VATS will likely face a steeper learning curve than their colleagues who are considered 'masters' at this approach who then go on to train in robotics, and as such, case volumes to gain proficiency will vary. The majority of studies in the literature selected for surgeons with good background experience in VATS, assuming they would be the best operators to transition across to robotic approaches, but no clear definition of what constituted acceptable prior experience was provided. Aggregation of specific learning curve outcomes (i.e., operative time reductions) was also not possible given the different metrics investigators utilized.

CUSUM analysis was utilized for five studies (13,15,18,21,29), whereas other studies report trendline regression (similar in principle to CUSUM) (9) or plateaus in improvement across specific outcomes (10-12,19). To the author's knowledge, there are no means of aggregating these statistical methods, other than through accepting their individual constraints, and aggregating them as a whole. Additionally, analysis of single and multi-surgeon outcomes was aggregated, introducing a degree of inter-rater variability. However, stratifying for single versus multi-surgeon outcomes would too heavily restrict case volumes so as to render aggregation inappropriate. Complexity of pathology was not homogenized across consecutive cases, which is reflected in a bimodal distribution and/or plateauing of operating time in several studies (20,28). The overwhelming majority of the studies included were also retrospective in nature, with the inherent risks of biases entailed in such a study design. This was assessed to as pragmatic a degree as possible.

Conclusions

The robotic-assisted lobectomy has been illustrated to have a reasonable learning curve profile based on the existing literature. For those operators with prior experience in minimally invasive surgery, it is likely that the learning curve will be more forgiving as opposed to a novice, though this is not as critical as is thought. Current evidence on the oncologic efficacy and purported benefits of the robotic approach, including reducing inpatient stay and rates of complication, will be bolstered by upcoming randomized trial results and will be critical in confirming its role as a needed approach in the management of thoracic malignancies.

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Footnote

Conflicts of Interest: The authors have no conflicts of interest to declare.

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Supplementary

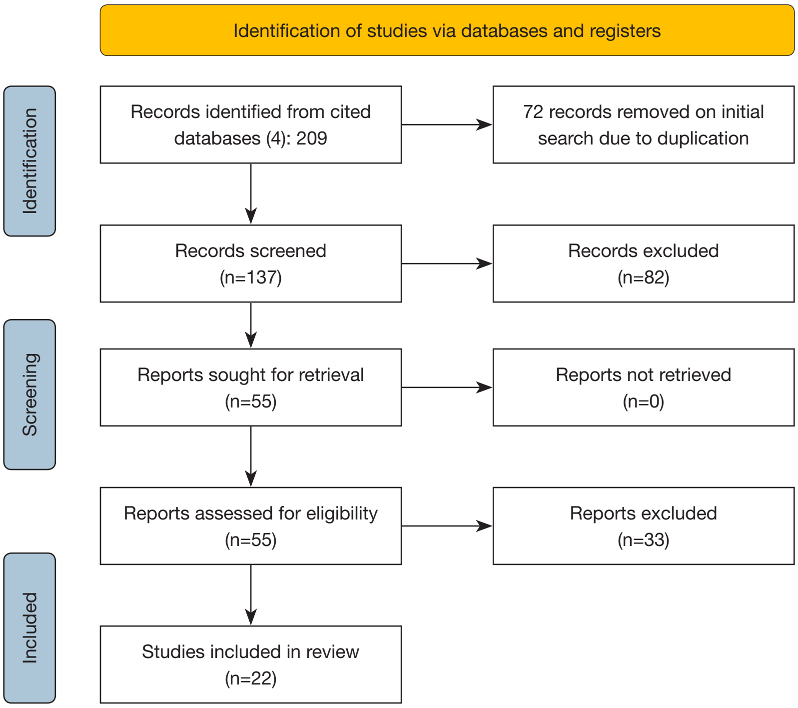

Figure S1 PRISMA flow chart.

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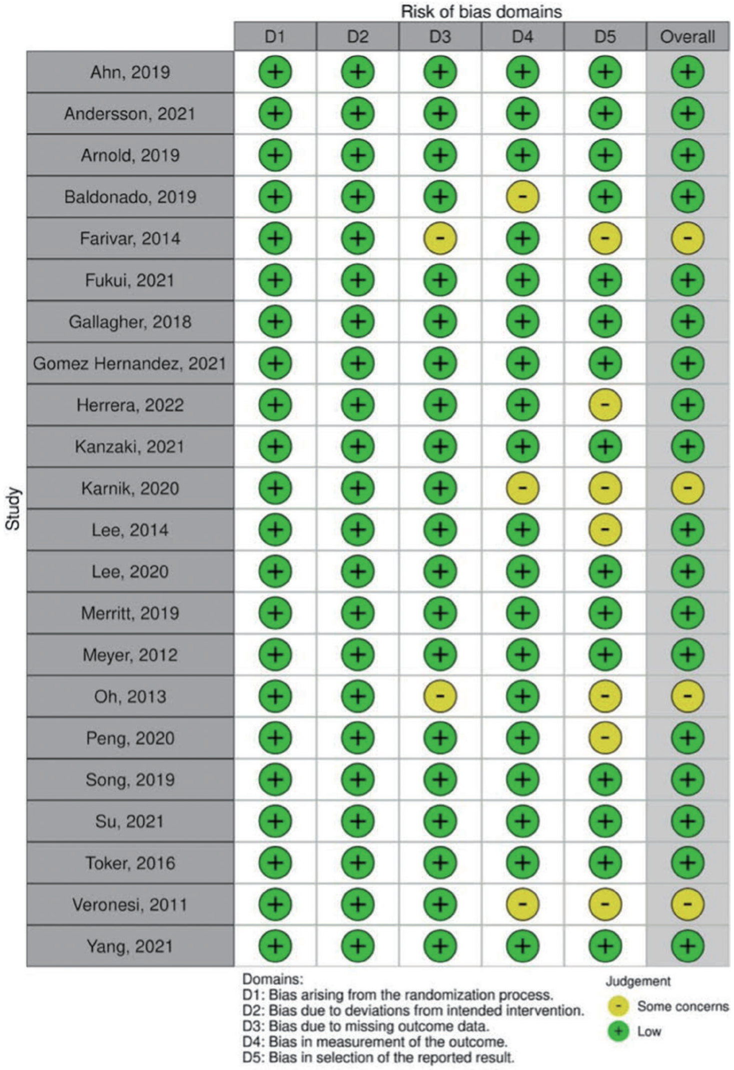
Table S1 Canadian Institute of Health Economics Quality Appraisal Checklist for Case Series (modified)

Domain	Description
1	Was the hypothesis/aim/objective of the study clearly stated?
2	Was the study conducted prospectively?
3	Were the cases collected in more than one center?
4	Were the patients recruited consecutively?
5	Were the characteristics of the patients included in the study described?
6	Were the eligibility criteria for entry into the study clearly described?
7	Did the patients enter the study at a similar point in their disease?
8	Was the intervention of interest clearly described?
9	Were additional interventions clearly described?
10	Were relevant outcome measures established a priori?
11	Were the outcomes appropriately measured?
12	Were the relevant outcome measures made before and after the treatment?
13	Were the statistical tests used appropriate for the outcome of interest?
14	Was follow-up long enough for important events and outcomes to occur?
15	Were losses to follow-up reported/
16	Did the study provide estimates of random variability in the data?
17	Were the adverse events reported?
18	Were the conclusions of the study supported by the results?
19	Were the competing interests and support sources reported?



Risk of bias domains

Study	D1	D2	D3	D4	D5	Overall
Ahn, 2019	+	+	+	+	+	+
Andersson, 2021	+	+	+	+	+	+
Arnold, 2019	+	+	+	+	+	+
Baldonado, 2019	+	+	+	-	+	+
Farivar, 2014	+	+	-	+	-	-
Fukui, 2021	+	+	+	+	+	+
Gallagher, 2018	+	+	+	+	+	+
Gomez Hernandez, 2021	+	+	+	+	+	+
Herrera, 2022	+	+	+	+	-	+
Kanzaki, 2021	+	+	+	+	+	+
Karnik, 2020	+	+	+	-	-	-
Lee, 2014	+	+	+	+	-	+
Lee, 2020	+	+	+	+	+	+
Merritt, 2019	+	+	+	+	+	+
Meyer, 2012	+	+	+	+	+	+
Oh, 2013	+	+	-	+	-	-
Peng, 2020	+	+	+	+	-	+
Song, 2019	+	+	+	+	+	+
Su, 2021	+	+	+	+	+	+
Toker, 2016	+	+	+	+	+	+
Veronesi, 2011	+	+	+	-	-	-
Yang, 2021	+	+	+	+	+	+

Domains:
D1: Bias arising from the randomization process.
D2: Bias due to deviations from intended intervention.
D3: Bias due to missing outcome data.
D4: Bias in measurement of the outcome.
D5: Bias in selection of the reported result.

Judgement
- Some concerns
+ Low

Figure S2 ROBINS visual representation tool.