Original Article

Defining the optimal annual institutional case volume for minimally invasive repair of pectus excavatum through a systematic review of literature and meta-analysis of outcomes

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Background: The Nuss procedure is the accepted standard approach to correct pectus excavatum. Still, is associated with potential major complications that are in part believed to be preventable as they might be the consequence of institutional case-volume differences. The objective is to evaluate the presence of a volume-outcome relation for the Nuss procedure and determine the optimal annual institutional case-volume threshold, defining high-volume centers.

Methods: A systematic literature search was performed, considering studies from unique centers reporting on pectus excavatum patients who underwent the Nuss procedure. Primary and secondary outcomes were, respectively: the incidence of significant perioperative complications (Clavien-Dindo ≥ grade-III and significant intraoperative complications) and bar displacement. The presence of a non-linear volume-outcome relation was evaluated through restricted-cubic-spline-analyses. If present, the optimal annual institutional case-volume was determined by the elbow method.

Results: Forty-nine studies from 49 unique centers were included, enrolling 13,352 patients in total. The significant perioperative complication rate was low [7.7%, 95% confidence interval (CI): 6.4–9.0%] and demonstrated a significant non-linear volume-outcome relation ($P<0.001$), even after covariate adjustment. The optimal annual institutional case-volume was determined at 73 cases/year (95% CI: 67–89). In this scenario, the number needed to treat to prevent a single perioperative complication compared to a low volume center was 11 (95% CI: 8–19). A similar volume-outcome relation ($P<0.001$) and optimal case volume of 73 cases/year was observed for bar displacement.

Conclusions: A significant volume-outcome relation for repair of pectus excavatum by the Nuss procedure exists with an optimal annual institutional case-volume of 73 cases/year. These findings provide rationale for centralization.

Keywords: Pectus excavatum; Nuss procedure; systematic review; volume-outcome; case volume

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Introduction

Minimally invasive repair by the Nuss procedure is the accepted standard approach for surgical correction of pectus excavatum. It has been associated with reduced operative time, surgical trauma, blood loss (1), and costs (2) as compared to the conventional open Ravitch procedure. Still, the Nuss procedure is associated with potential major complications. These complications are in part believed to be preventable (3), and might be the consequence of the learning curve (3-6) or annual institutional case volume differences (7,8). For example, Linton and colleagues previously observed that the probability of a complication was lower for centers in the fourth quartile based on an annual case load (7). Under the assumption of such a relation, surgical treatment of pectus excavatum may ideally be performed in dedicated high volume centers. Still, the actual definition of such a center—in terms of the main criterion: annual case volume (9)—is yet to be defined for the Nuss procedure.

Recently, Kawczynski and colleagues proposed a novel approach to establish the presence of a volume-outcome relation and define the optimal annual case volume for cardiovascular interventions. The latter is considered the point at which additional case load no longer significantly improves outcome and can be applied to define centers of excellence (10). Eventually, these developments may provide rationale for centralization of pectus excavatum care, with the ideal to concentrate multidisciplinary expertise and improve patient quality of care (11).

In the absence of established (inter)national registries on the outcomes after the Nuss procedure, the purpose of the present study is to apply novel statistical methods to establish the volume-outcome relation for the Nuss procedure and determine the optimal annual institutional case volume threshold by conducting a review of literature and meta-analysis of outcomes. We present this article in accordance with the PRISMA reporting checklist (available at https://jtd.amegroups.com/article/view/10.21037/jtd-24-690/rc) (12).

Highlight box

Key findings

- A significant volume-outcome relation for repair of pectus excavatum by the Nuss procedure exists with an optimal annual institutional case-volume of 73 cases/year.

What is known and what is new?

- The Nuss procedure is the accepted standard approach to correct pectus excavatum. However, it is still associated with potential major complications. These are in part believed to be preventable and might be the consequence of institutional case-volume differences. Yet, such a relationship is still to be established.
- Therefore, we evaluated the presence of a volume-outcome relation for the Nuss procedure and determined the optimal annual institutional case-volume threshold, aiming to define a so-called center of expertise or high-volume center.

What is the implication, and what should we change now?

- In line with the above recommendations, a discussion should be initiated among health care providers about whether centralization of pectus excavatum care would benefit outcomes. The findings of this study could provide guidance in this discussion.

Methods

Design

The present study was designed as a systematic review to evaluate the volume-outcome relation for minimally invasive repair of pectus excavatum through the Nuss procedure. Prior to start, a local review protocol was drawn.

Eligibility criteria

No publication date restrictions were imposed. Though, studies at least needed to report on (I) the enrollment period; (II) the number of consecutive patients who underwent the Nuss procedure; and (III) the primary outcome measure being clinically significant perioperative complications [defined as: all complications requiring reintervention (Clavien-Dindo classification 3a and 3b), intensive care unit (ICU) admission (Clavien-Dindo classification 4), mortality (Clavien-Dindo classification 5), and all significant intraoperative complications such as pericardial and myocardial damage or damage to major vascular structures (13)]. See Table S1 for a comprehensive overview of all complications that were considered as primary outcome.

Single-center studies were eligible as they allowed for reliable determination of the institution's annual caseload. Multi-center studies were included only if the data were presented separately for each institution. Duplicate studies of the same center in overlapping time period were avoided by only including the study describing the largest sample size of that specific institution.

Studies that reported on a subset or selection of patients (for example: only patients who received a single bar during the Nuss procedure or patients of set ages) were excluded because they did not accurately reflect the actual number of annual case load. Though, studies that only included pediatric patients on the condition that the specific center was a children's hospital (age limit: equal to or younger than 18 years of age).

No distinction was made between studies reporting on operative results with a slight modification of the original Nuss technique (e.g., alternative fixation method or additional use of sternal elevation techniques) or the original Nuss technique itself, anticipating the natural movement of procedural changes over time to optimize patient outcome. Studies involving open surgical repair of pectus excavatum, or minimally invasive repair through an extrapleural approach were excluded. In addition, studies reporting on concomitant interventions during the same surgical session were excluded. To ensure homogeneity, while obtaining a good reflection of the daily clinical practice, a maximum of 5% of patients who underwent prior surgical treatment for pectus excavatum was allowed. This percentage was arbitrarily chosen. At last, case reports and case series (a threshold of at least 10 participants was arbitrarily applied) were excluded together with (conference) abstracts.

Search and study selection

Potentially eligible studies were explored by searching electronic scientific databases. Only studies reported in English were considered. Search terms were applied to the title and abstract fields. Search strategy was first constructed for PubMed (searched through the National Library of Medicine) and subsequently adapted for EMBASE (OvidSP). See Tables S2,S3 for the applied search queries. An additional manual cross-reference and related articles search was conducted. This additional search served as an indicator of the quality and completeness of the database search strategy. All database searches were performed by a librarian-trained researcher (J.H.T.D.). The last search was performed on June 24th, 2023. Duplicates were discarded whereupon the remaining non-duplicate articles were judged for potential eligibility based on their title and abstract. Thereafter, full text of potentially eligible articles was read and assessed according to the predefined eligibility criteria. Studies meeting these criteria were included for review and analysis. Study selection was performed in a blinded, standardized manner by two independent reviewers (J.H.T.D. and I.C.), using the web-based application Rayyan (http://rayyan.qcri.org) (14). Inter-reviewer disagreements were resolved by consultation of the senior author (E.R.d.L.).

Data collection

Data was manually extracted by two reviewers (J.H.T.D. and I.C.), using a pre-defined worksheet (Table S4), and cross-checked for validity through random study selection. Inter-reviewer disagreements were resolved by consultation of the senior author (E.R.d.L.). Next to the below-mentioned primary and secondary outcome measures, the following data was extracted from each included study: (I) study characteristics: study design, country, city, institution, enrollment period (January and December were respectively selected for the lower and upper boundary if only the years of enrollment were reported), length of postoperative follow-up, and year of publication; (II) patient characteristics: age, sex, Haller index, and prior surgical treatment for pectus excavatum (specified according to the technique used); and (III) characteristics of the intervention: duration of surgery and length of hospital stay.

Outcomes and effect measures

The primary outcome measure was the incidence of clinically significant perioperative complications [defined as: all complications requiring reintervention (Clavien-Dindo classification 3a and 3b), ICU admission (Clavien-Dindo classification 4), mortality (Clavien-Dindo classification 5), and all significant intraoperative complications such as pericardial and myocardial damage, or damage to major vascular structures (13)] in relation to the annual hospital case volume as assessed by restricted cubic spline analysis (see data synthesis). The secondary outcome measure was the incidence of bar displacement regardless of the need for revisional surgery. See Table S1 for a comprehensive overview of definitions and complications considered as outcome. Included studies were divided in quartiles (Qs; Q1–Q4) based on annual case volumes. Annual case volume in relation to the outcome measures (cases/year on the x-axis; percentage including variance on the y-axis) was presented graphically and in tabular form (with respect to a case volume of 10 cases/year). For the latter, the absolute-, relative risk reduction (ARR and RRR), and number needed to treat (NNT) to prevent a single perioperative complication in a high- compared to a low-volume center were calculated.

Study quality assessment

The present study was not designed to evaluate differences between groups but aimed to evaluate outcomes of the Nuss procedure in relation to the annual case volume in a whole group fashion. As a result, conventional risk of bias assessment tools may not apply. Yet, to objectively assess the risk of bias in individual studies, the Newcastle-Ottawa scale was modified (removal of question 2 in selection) to accommodate assessment of single-arm studies, as previously described (15). A rating between 0 and 2 was graded as poor quality, while scores 3–5 and 6–8 were, respectively, graded as fair and good quality. Quality assessment was performed by two authors (J.H.T.D. and I.C.).

Data synthesis

Studies reporting continuous variables as mean and standard deviation (SD) were extracted. If necessary, conversion was applied according to Wan's method (16). Patient characteristics and procedural characteristics were presented per quartile. Between-quartile differences were evaluated by the Chi-squared test for categorical variables and one-way analysis of variance for continuous variables, based on weighted summary data. Per quartile outcome measures were presented as pooled weighted averages (DerSimonian and Laird method with random-effects model).

Statistical analyses

For the primary analyses, the principles of Kawczynski *et al.* [2023] were applied (10). The potential non-linear relation between annual case volume and outcome was evaluated by a restricted cubic-spline model for meta-analysis using three knots (non-linear mixed effects model) and presented graphically. Institution specific weights were assigned based on the variance of data (graphically, a relatively larger diameter of the sphere indicates increased weight due to less variance). The primary outcome was adjusted for covariates on a study-level in a linear regression model (17). Covariates adjusted for included the patients' age [since increasing age is associated with higher risk of complications (18)] and publication year [since evolving techniques and experience contributed to a decrease in the frequency of bar-related complications over time (19)]. The optimal annual case volume was derived using the elbow-method (20). This optimal volume represents the minimal required case load after which the accrual of additional cases does not lead to a statistically significant improved outcome rate, defining a high volume center. The volume-outcome relation was expressed in terms of the primary outcome (%) and 95% confidence interval (CI). To facilitate profound clinical interpretation of the volume-outcome relation, the ARR, RRR and NNT were calculated for fixed annual case volumes, using a volume of 10 cases per year as reference. All statistical analyses were performed using R statistics (R Foundation, version 3.6.0., Vienna, Austria).

Publication bias assessment

The probability of publications bias was explored both visually by a funnel plot and statistically by Egger's linear regression test, using a P value of <0.05 to indicate the presence of statistically significant publication bias. This probability was explored for the primary outcome measure.

Results

Study selection

The process of study selection is depicted by the PRISMA flow diagram in *Figure 1*. The systematic search yielded a cumulative number of 1,339 studies, of which 1,225 remained after duplicate removal. An additional 992 were excluded based on their title and abstract, leaving 233 articles for full-text screening of which 22 could not be retrieved. Eventually, 49 studies were included for final analysis after exclusion of another 162 studies due to various reasons as described in *Figure 1*.

Study characteristics

The 49 included studies originated from 49 unique institutions (5 continents, 21 countries). Forty-six studies (94%; n=46/49) had a retrospective observational design. A cumulative number of 13,352 patients undergoing the Nuss procedure were included. Individual sample sizes ranged from 11 to 1,713 patients (*Figure 2A*). The annual case volume ranged from 1 to 259 cases per year (*Figure 2B*). See *Figure 2C* for the geographical distribution. Individual study characteristics are presented in Table S5.

Patient and interventional characteristics

Patient and interventional characteristics are presented in *Table 1* for the overall cohort and per study in Table S6.

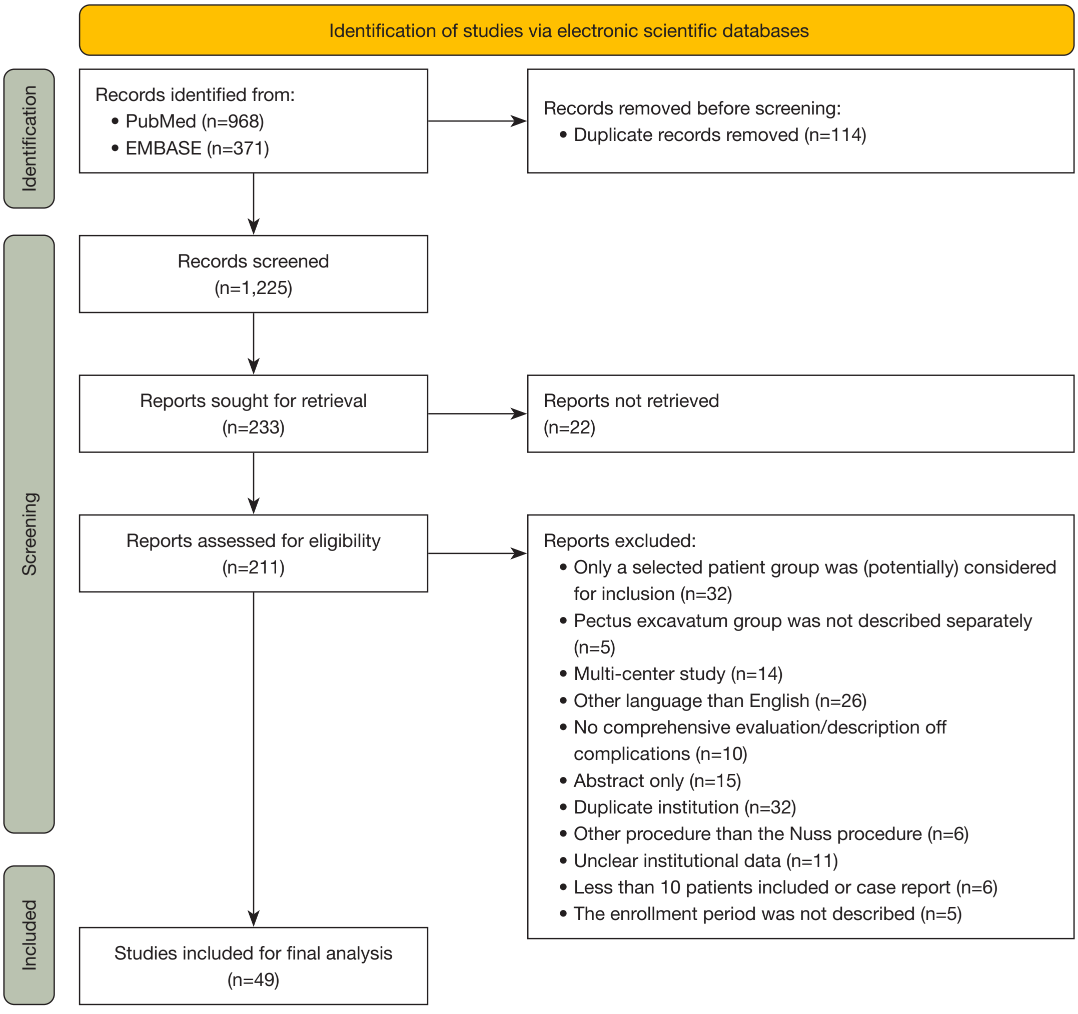

Figure 1 Preferred reporting items for systematic reviews and meta-analyses flow chart depicting the process of study selection.

A cumulative number of 13,352 patients were enrolled. The mean age of the population was 14.5 years (SD: 8.4; n=13,059; 45 studies) of whom 82% were male (n=9,576/11,726; 43 studies). The severity of the deformity, as expressed by the mean Haller index was 4.7 (SD: 5.4; n=9,034; 28 studies). Neither of these characteristics did significantly differ for patients in Q1 to Q4. A total of 156 patients underwent corrective surgical treatment prior to the evaluated Nuss procedure with the highest incidence in Q4. The mean duration of surgery was 57 minutes (SD: 44; n=8,239; 27 studies) with a postoperative length of hospital stay of 5.5 days (SD: 3.4; n=8,374; 35 studies), revealing statistically significant inter-quartile differences (P<0.001). Both the duration of surgery and hospital stay were lowest for Q4 (49 minutes, SD: 46; and 5.4 days, SD 2.2, respectively).

Study quality assessment

The overall study quality ranged from fair (12 studies) to good (37 studies). The main factor limiting quality was the missing control for covariates. The quality per individual study can be appreciated in Table S7. No studies were excluded based on quality assessment.

Synthesis of results

Primary outcome: clinically significant perioperative complications

The incidence of clinically significant perioperative

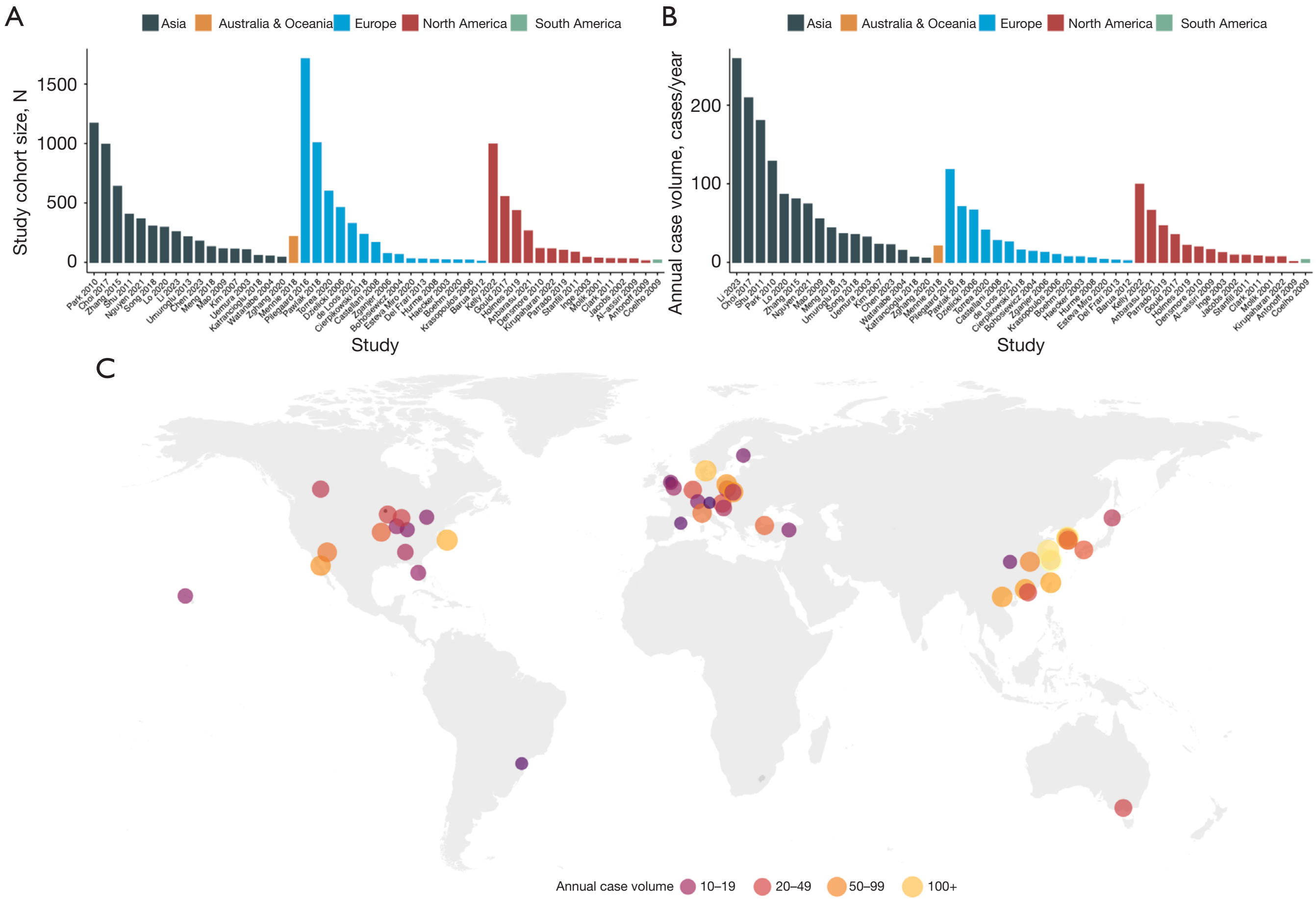

Figure 2 Study sample sizes and geographical distribution. (A) Study sample sizes, (B) annual case volume per included center, and (C) the geographical distribution of included centers.

complications was 7.7% (95% CI: 6.4–9.0%) for the entire cohort and differed between all four quartiles (n=13,352; 49 studies) with the incidence being lowest in the quartile with the highest annual case volume [5.1% (95% CI: 3.3–7.0%, Q4) *vs.* 14.7% (95% CI: 9.0–20.5%, Q1); *Table 1*].

The median institutional incidence of clinically significant perioperative complications was 8.8% (95% CI: 6.3–11.2%) corresponding to a modelled annual institutional volume of 36 cases per year.

A significant non-linear association was observed between the annual case volume and clinically significant perioperative complications (P<0.001; *Figure 3A*). This association was also observed after adjustment for covariates (year of publication and patient age; P=0.047; *Figure 3B*). By virtue of the elbow method, the optimal annual case volume (i.e., the minimal required case load after which the accrual of additional cases does not lead to a statistically significant improved outcome rate) was determined at 73 cases per year (95% CI: 67–89; *Table 2*; *Figure 3A*). In this scenario, the ARR is 8.8% (95% CI: 5.4–12.2%), RRR is 63.3% (95% CI: 38.8–87.8%) and the NNT to prevent a single significant complication is 11 patients (95% CI: 8–19; compared with an annual case volume of 10 cases per year; *Table 2*). This implies that a single significant complication can be prevented per every 11 patients who undergo the Nuss procedure at a so-defined high volume center performing an optimal number of cases annually.

Secondary outcome: bar displacement

The weighted frequency of bar displacement, including rotation and translation, regardless of the need for revisional

Table 1 Study characteristics, patient and interventional characteristics, and outcomes divided into annual case volume quartiles

	Overall	Quartile 1 [1 to 7 cases per year]	Quartile 2 [8 to 21 cases per year]	Quartile 3 [22 to 60 cases per year]	Quartile 4 [61 to 259 cases per year]	P value
Study characteristics						
Number of studies, n	49	12	12	13	12	NA
Number of patients, n	13,352	426	1,005	3,351	8,570	NA
Patient and interventional characteristics						
Sex						0.07
Male, n	9,576	336	675	2,389	6,176	
Female, n	2,150	55	171	526	1,398	
Not reported, n [%]	1,626 [12]	35 [8]	159 [16]	436 [13]	996 [12]	
Age, in years, mean [SD]	14.5 [8.4]	14.8 [5.3]	14.6 [4.6]	14.8 [6.5]	14.4 [9.4]	0.12
Not reported, n [%]	293 [2]	0 [0]	192 [19]	101 [3]	0 [0]	
Haller index, mean [SD]	4.7 [5.4]	4.4 [1.7]	4.4 [1.5]	4.6 [3.0]	4.8 [6.2]	0.30
Not reported, n [%]	4,318 [32]	245 [58]	857 [85]	985 [29]	2,231 [26]	
Prior treatment						<0.001*
Yes, n	156	1	8	22	125	
No, n	5,389	59	357	1,563	3,410	
Not reported, n [%]	7,807 [58]	366 [86]	640 [64]	1,766 [53]	5,035 [59]	
Duration of surgery, in minutes, mean [SD]	57 [44]	85 [31]	101 [39]	64 [35]	49 [46]	<0.001*
Not reported, n [%]	5,113 [38]	205 [48]	618 [61]	606 [18]	3,684 [43]	
Length of hospital stay, in days, mean [SD]	5.5 [3.4]	6.5 [3.6]	5.9 [2.5]	5.5 [4.7]	5.4 [2.2]	<0.001*
Not reported, n [%]	4,978 [37]	100 [23]	462 [46]	274 [8]	4,142 [48]	
Outcomes						
Clinically significant perioperative complications (%, 95% CI)	7.7 (6.4–9.0)	14.7 (9.0–20.5)	8.9 (6.1–11.7)	8.8 (6.7–11.0)	5.1 (3.3–7.0)	NA
Bar displacement (%, 95% CI)	2.1 (1.6–2.6)	5.1 (2.3–8.0)	2.2 (1.0–3.4)	2.8 (1.7–4.0)	1.5 (0.9–2.2)	NA

*, significant P values. NA, not applicable; SD, standard deviation; CI, confidence interval.

surgery, was 2.1% (95% CI: 1.6–2.6%). Bar displacement significantly differed between quartiles, being lowest for Q4 [1.5% (95% CI: 0.9–2.2%) *vs.* 5.1% (95% CI: 2.3–8.0%) for Q1]. Just as for the primary outcome, a significant non-linear relationship was observed between bar displacement and annual case volume (P=0.008; *Figure 4*). In addition, an identical optimal annual case volume of 73 cases per year was observed for bar displacement (*Figure 4*).

Publication bias assessment

Publication bias assessment through visual evaluation of the funnel plot indicated no evident presence of publication bias (see *Figure 5*). This finding was confirmed statistically by Egger's linear regression test (P=0.51).

Discussion

The present study evaluated the volume-outcome relation and optimal annual institutional case volume threshold for minimally invasive repair of pectus excavatum by the Nuss procedure. A significant volume effect was established for the primary and secondary outcome. Based on this non-linear relation between volume and significant perioperative

Table 2 Volume-outcome relationship for fixed annual case volumes (in steps of 10 cases per year and using 10 cases per year as reference) for the primary outcome: clinically significant perioperative complications

Annual case volume (cases/year)	Outcome retrieved from RCS for volume-outcome relation (*Figure 3A*)	Clinical estimates, as compared to an annual case volume of 10 cases/year		
	Mean (%, 95% CI)	ARR (%, 95% CI)	RRR (%, 95% CI)	NNT (95% CI)
10	13.9 (11.2–16.5)	Ref.	Ref.	Ref.
20	11.6 (9.6–13.7)	2.3 (0.2–4.3)	16.5 (1.4–30.9)	43 (23–500)
30	9.7 (7.5–12.0)	4.2 (1.9–6.4)	30.2 (13.7–46.0)	24 (16–53)
36	8.8 (6.3–11.2)	5.1 (2.7–7.6)	36.7 (19.4–54.7)	20 (13–37)
40	8.2 (5.5–10.8)	5.7 (3.1–8.4)	41.0 (22.3–60.4)	18 (12–32)
50	7.0 (3.9–10.0)	6.9 (3.9–10.0)	49.6 (28.1–71.9)	14 (10–26)
60	6.0 (2.7–9.3)	7.9 (4.3–11.2)	56.8 (30.9–80.6)	13 (9–23)
70	5.3 (2.0–8.7)	8.6 (5.2–11.9)	61.9 (37.4–85.6)	12 (8–19)
73	5.1 (1.7–8.5)	8.8 (5.4–12.2)	63.3 (38.8–87.8)	11 (8–19)
80	4.8 (1.4–8.2)	9.1 (5.7–12.5)	65.5 (41.0–89.9)	11 (8–18)
90	4.4 (1.1–7.8)	9.5 (6.1–12.8)	68.3 (43.9–92.1)	11 (8–16)
100	4.2 (0.9–7.5)	9.7 (6.4–13.0)	69.8 (46.0–93.5)	10 (8–16)

The annual case volume of 36 cases per year contained the median modelled incidence of clinically significant perioperative complications. Seventy-three cases per year was found to be the optimal annual institutional case volume at which the incidence of clinically significant perioperative complications started plateauing. RCS, restricted cubic spline; CI, confidence interval; Ref., reference; ARR, absolute risk reduction; RRR, relative risk reduction; NNT, number needed to treat (to prevent a single clinically significant perioperative complication).

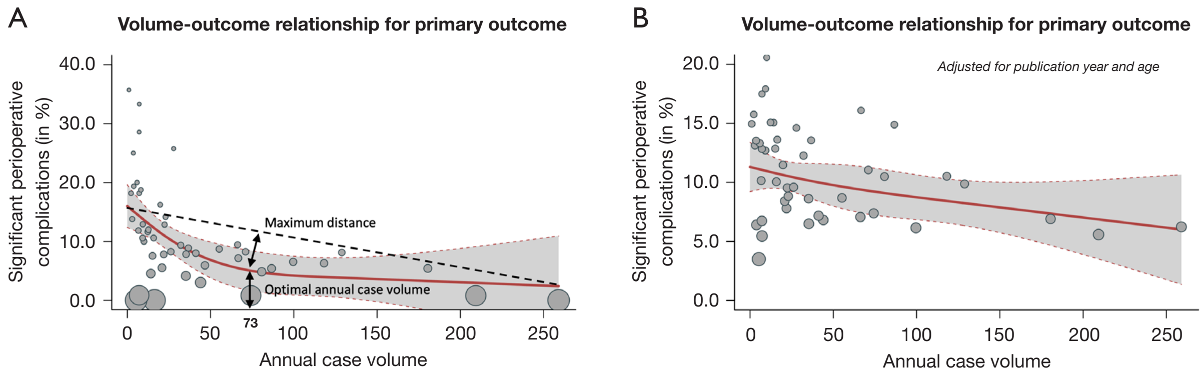

Figure 3 Volume-outcome relationship for (A) clinically significant perioperative complications, and (B) clinically significant perioperative complications adjusted for publication year and age. Here, relatively larger spheres indicate more weight given to that specific study due to less variance.

complications, as well as bar displacement, the optimal annual institutional case volume was determined at 73 cases per year. After this case load the accrual of additional cases did not lead to a statistically significant improved outcome.

In the past years, several studies have endeavored to identify a volume-outcome relation for pectus excavatum treatment and stratify centers based on their annual case load. Linton and colleagues evaluated 47 pediatric centers including a cumulative number of 7,183 patients, though no distinction was made between the method of repair. They stratified centers according to quartiles with an annual case load of more than 26 cases per year in Q4—revealing lower odds of encountering a complication (7). Although an equivalent volume-outcome relation was observed in the present study, even after adjusting for covariates, the optimal annual institutional case volume was determined to be considerably higher than 26 cases per year given the non-linear relation between volume and outcome. In

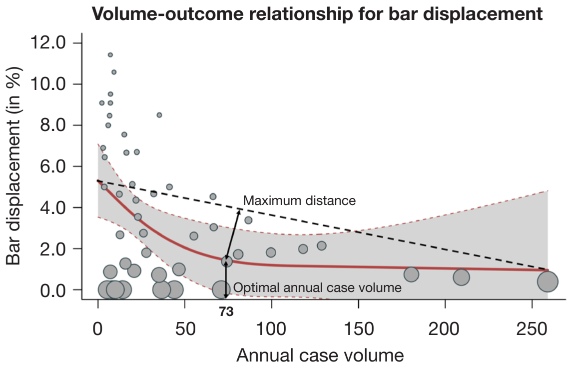

Figure 4 Volume-outcome relationship for bar displacement. Here, relatively larger spheres indicate more weight given to that specific study due to less variance.

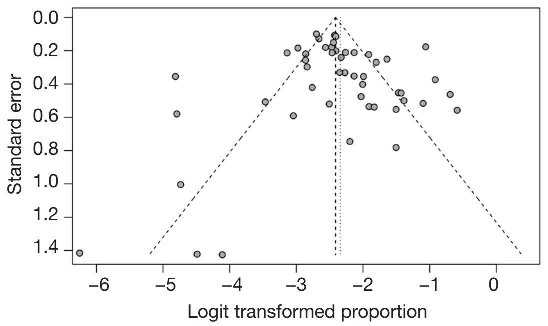

Figure 5 Assessment of publication bias by means of a funnel plot for the primary outcome.

contrast, Mack and colleagues retrospectively evaluated a national United States database incorporating 360 pectus patients from 148 unique centers. They defined a high volume center as a center which performed more than the mean number of patients per facility, i.e., 7 cases per year, and surprisingly observed favorable outcomes in terms of complications and costs for procedures performed at low volume centers (i.e., less than 7 cases per year) (21). Despite their efforts, this study was limited by relative sample size and lacked adequate statistical methods.

With respect to the volume-outcome effect, other outcome measures may also be appreciated. The length of postoperative hospital stay revealed a declining trend with increasing annual institutional case volume as depicted by the quartiles [6.5 days (SD: 3.6) for Q1 *vs.* 5.4 days (SD: 2.2) for Q4]. However it must be noted that up to 48% of data was missing per quartile. In addition, although the decreasing length of hospital stay may intuitively be a positive effect of increasing volume, it is also subject to secondary factors, including pain management protocols, the number of operating surgeons, dedication and care pathway optimization, and specific local preferences (21). For example, the recent increase in use of cryoanalgesia has induced a significant reduction in length of hospital stay (22) and does nowadays even allow same-day discharge (23). These factors could also rationalize the non-linear trend in operation time since, using the same example, thoracoscopic cryoanalgesia significantly increases the duration of surgery compared to thoracic epidural analgesia (22).

In addition, it is a natural motion that one operates more difficult cases with increasing experience. This often concerns older patients (21) which exhibit more difficult corrections due to their relatively higher chest wall rigidity. Such corrections generally require multiple bars (24) and are associated with an increased complication rate (8), including pain (25). However, this was not observed in the present study: the mean age distribution was comparable among Q1–Q4, and the volume-outcome relation persisted even after correction for age.

Implications and considerations

Centralization of health care services is one of the major contemporary themes in current health care policy (26). The general rationale for centralization is to concentrate multi-disciplinary expertise, improve the quality of care and increase health care efficiency, while decreasing expenses (11). This may be of particular importance to relatively uncommon thoracic diseases and procedures, such as for pectus excavatum, as elaborated in the present study. Annual institutional case load is considered the most important criterion to define a center of expertise. This is based on the hypothesis that adverse outcomes are minimized with accumulation of case load while optimizing efficiency. In England, pectus care has already been initiated to be centralized in two-to-three so-called specialist centers (27). We believe that the results of the present study can provide further guidance. In the present study, we observed an important relation between volume and outcome for the Nuss procedure and were able to determine an optimal annual institutional case volume (73 cases per year, 95% CI: 67–89) for this procedure. Although the potential benefits regarding the risk of significant perioperative complications are clear when performing the Nuss procedure in centers with such a case load (ARR 8.8%, 95% CI: 5.4–12.2%), other aspects should also be considered regarding centralization.

A high volume center should preferably treat the whole spectrum of anterior chest wall diseases and offer the entire pallet of treatments, both surgical (e.g., Nuss procedure, Ravitch procedure, Abramson procedure) and non-surgical (e.g., bracing therapy, vacuum bell therapy). In addition, one should institute a dedicated team, comprising of cardiologists, pulmonologists, surgeons, orthotic specialists, pediatricians, and surgeons, based in a specialized chest wall unit (28). Decision-making through such a team-based approach may facilitate optimal patient selection for the different treatment options, including the Nuss procedure. Establishing such a dedicated team may also be a step forward toward standardization as a partial solution to the significant inter-observer and intra-observer disagreements regarding pectus excavatum, as highlighted earlier (29).

Centralization of pectus excavatum care could also warrant the availability of multimodality imaging techniques. Although standard imaging techniques suffice for most patients, advanced techniques such as magnetic resonance augmented cardiopulmonary exercise testing (30), four-dimensional transesophageal echocardiography (31), and three-dimensional imaging (32,33) could be of added value. The same goes for other advanced techniques, such as the use of cryoanalgesia for pain management.

Although one of the incentives for centralization is to cut costs, there is no current scientific evidence supporting this for pectus excavatum (7,21). However, it must be noted that these studies did not apply the optimal volume threshold as determined in the present study.

In 2019, the National Health Service (NHS) of England published a statement that there is not enough evidence to routinely commission treatment of pectus excavatum (34). It was stated that the body of clinical evidence is largely limited to non-randomized reports with relatively small sample sizes and significant heterogeneity. As such, the systematic reviews and meta-analyses of these observational studies were at risk of significant confounding and bias. In addition, the absence of standardized measures to weigh clinical benefits against the surgery related morbidity presented a challenge to provide conclusions on the benefits of an intervention. Although, in 2023, the NHS proceeded an urgent policy statement, recommending pectus surgery to only be available for patients with pectus excavatum resulting in very severe physiological symptoms, the foregoing remains true (27). Here, centralization can be of significant value providing the opportunity to conduct powered studies in a homogeneous environment.

Scrutinizing centralization of pectus care, one should not only consider the annual institutional volume, but also account for the geographical distribution of centers and socioeconomic disparity.

Finally, the bulk who undergo repair of pectus excavatum concern patients of adolescent age, as also indicated by the mean age of the overall cohort (14.5 years, SD: 8.4). As the indication to perform surgery also embraces pure psychosocial complaints, surgical risk should be reduced to a minimum. (Disabling) complications can have a devastating impact on the quality of life and lifetime health care expenses. Furthermore, a durable result of repair is of utmost importance, as surgical repair restores both physical and psychological quality of life (35). Eventually, centralization of pectus excavatum care in high volume centers, as elaborated by this study, may facilitate, and enhance these outcomes.

Limitations

By nature, centers with suboptimal results or relatively low case load are less inclined to report their experience, raising the potential of publication bias. As a result, the actual optimal annual case volume could be higher than 73 cases per year. Still, no evident presence of publication bias was indicated through analyses. Notwithstanding, multicenter studies (n=14) were excluded introducing potential publication bias. In addition, centers generally do not report on their ongoing experience, duly some of the data evaluated may be considered dated.

Overall, the study quality was relatively good with 76% (n=37/49) of studies being categorized as of "good" quality according to the adapted Newcastle Ottawa Scale. Besides the missing control for covariates, the second most limiting factor of study quality was the length and adequacy of follow-up (see Table S7). Some of the studies did not mention the length nor adequacy of follow-up, which may have underestimated the real complication rate during the postoperative period. In addition, a time-to-event analysis would have added value to the current study, but it was not reported by any of the individual studies. Nor was it always clear how complications were handled and whether they concerned single complications in unique patients.

For the sake of homogeneity, studies involving open surgical repair of pectus excavatum were excluded, along with those through a minimally invasive extrapleural approach. We recognize that a variety of adaptations have been made to the Nuss procedure over time. Yet, given the great diversity and magnitude of adaptations made, it was not possible to evaluate the precise effect of these adaptations on the outcomes.

To determine the volume threshold, literature-derived annual institutional case volumes were used. Evaluation of volume thresholds should ideally come from well-maintained (inter)national registers. However, since there are no such established registries, we must make do with the next best solution, considering the possibility of bias.

In addition, as annual institutional volume thresholds can be applied as one of the criteria guiding centralization, the volume of individual surgeons should ideally be considered instead of hospital volume. Yet, none of the studies did report on individual surgeons and their outcomes. Furthermore, considering individual surgeon volume, the individual learning curve must conjointly be acknowledged (4).

Conclusions

Minimally invasive repair of pectus excavatum by the Nuss procedure is associated with a significant non-linear relation between annual institutional case volume and outcome. Using optimization statistics, the optimal annual institutional case volume was determined at 73 cases per year, defining a high volume center. These findings could provide guidance in the discussion about centralization of pectus excavatum care and improve overall quality.

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Footnote

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