

Program Maturation Across 364 Robotic Colorectal Procedures: Postoperative Recovery, Operative Efficiency, and Major Morbidity

Igor Monsellato

igor.monsellato@ospedale.al.it

SCDU Chirurgia Generale, AOU SS. Antonio e Biagio e Cesare Arrigo

Marco Palucci

SCDU Chirurgia Generale, AOU SS. Antonio e Biagio e Cesare Arrigo

Fabio Giannone

SCDU Chirurgia Generale, AOU SS. Antonio e Biagio e Cesare Arrigo

Fabiana Marotta

SCDU Chirurgia Generale, AOU SS. Antonio e Biagio e Cesare Arrigo

Mariantonietta Alagia

SCDU Chirurgia Generale, AOU SS. Antonio e Biagio e Cesare Arrigo

Marco Lodin

SCDU Chirurgia Generale, AOU SS. Antonio e Biagio e Cesare Arrigo

Gianluca Cassese

SCDU Chirurgia Generale, AOU SS. Antonio e Biagio e Cesare Arrigo

Research Article

Keywords: robotic colorectal surgery, program maturation, length of stay, operative time, major morbidity, learning curve

Posted Date: September 30th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11028906/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Robotic colorectal learning-curve studies commonly define proficiency using operative time or cumulative-sum thresholds, which may not capture maturation of a heterogeneous program. We analysed 364 consecutive robotic colorectal procedures from a single-surgeon, single-centre program using prior global robotic colorectal experience as a continuous exposure. Principal clinical outcomes were postoperative length of stay (LOS) and major morbidity (Clavien-Dindo grade III or higher); operative duration was the principal process/efficiency outcome. Multivariable log-linear models adjusted for procedure family, robotic platform, associated procedures, age, and American Society of Anesthesiologists (ASA) class; major morbidity was analysed with Firth penalized logistic regression. Each doubling of (1 + prior experience) was associated with 5.1% shorter LOS (95% CI 2.2%-7.9% shorter; $p < 0.001$) and 5.3% shorter operative duration (95% CI 3.3%-7.4% shorter; $p < 0.001$). Restricted cubic spline analysis showed no evidence of LOS non-linearity ($p = 0.621$) but significant non-linearity for operative duration ($p < 0.001$), indicating a non-constant efficiency trajectory. Major morbidity occurred in 15/364 procedures (4.1%); the adjusted Firth odds ratio was 1.48 per experience doubling (95% profile-likelihood CI 0.84–3.64; $p = 0.208$). Because cumulative experience and calendar time were essentially collinear, estimates represent longitudinal program maturation rather than an isolated causal surgeon-experience effect. Program maturation was therefore associated with improved recovery and operative efficiency, while major morbidity remained uncommon but imprecisely estimated longitudinally.

Introduction

Robotic surgery has become an established component of contemporary colorectal practice, but adoption is not synonymous with maturation. The technical demands of robotic colorectal surgery vary substantially across right- and left-sided colectomy, transverse or splenic-flexure resection, and rectal surgery, while performance is also shaped by prior minimally invasive experience, case complexity, training structure, team familiarity, and the robotic platform itself. Most learning-curve studies have therefore focused on the number of cases required to reach a defined level of technical proficiency, commonly using operative time, console time, cumulative-sum (CUSUM) analysis, or risk-adjusted CUSUM. Systematic reviews, however, show wide variation in reported inflection points and emphasize that a single numerical proficiency threshold is highly dependent on procedure type, study size, case mix, prior experience, and the outcome used to define proficiency [1–3].

Recent studies have reinforced both the usefulness and the limitations of threshold-based learning curve analysis. Single-surgeon and multicentre series have demonstrated procedure-specific changes in operative efficiency, with different trajectories for colon and rectal resections and with safety curves that do not necessarily mirror time-based curves [4–9]. Contemporary reviews likewise show that operative time remains the dominant endpoint, whereas conversion, morbidity, pathological quality, and other patient-centred outcomes are incorporated less consistently [1, 10]. This matters because an operation becoming faster does not, by itself, establish that a program has become clinically better. For a mature, heterogeneous colorectal service, the relevant question is broader: whether accumulated program

experience is accompanied by measurable improvement in recovery while severe morbidity is characterised as a distinct safety domain.

Program maturation also extends beyond the individual console surgeon. Standardisation of port placement and operative steps, bedside assistance, anaesthetic practice, theatre workflow, nursing familiarity, postoperative pathways, case selection, and platform transition evolve over time and may influence both process and clinical outcomes. Structured program implementation has been associated with reproducible short-term results, and studies integrating enhanced recovery pathways or comparing different institutional robotic adoption phases suggest that length of stay can change alongside technical efficiency [11–17]. Length of stay (LOS) is therefore a clinically relevant complement to operative time: although influenced by complications and perioperative pathways, it captures the downstream consequence of the entire operative episode. Major morbidity provides a separate safety domain that should not be assumed to improve merely because efficiency improves.

We therefore evaluated longitudinal maturation across a consecutive 364-procedure robotic colorectal program using accumulated global robotic colorectal experience as a continuous exposure rather than dividing the series into arbitrary early and late phases. The principal clinical outcomes were postoperative LOS and major morbidity, while operative duration was treated as the principal process/efficiency outcome. We hypothesised that increasing program experience would be associated with shorter LOS and shorter operative duration, while severe morbidity would remain uncommon. Because accumulated experience and calendar time are intrinsically coupled in a longitudinal program, the analysis was designed to estimate a program-maturation association rather than a causal effect attributable solely to individual surgeon learning.

Methods

Study design and cohort

This retrospective longitudinal cohort comprised 364 consecutive robotic colorectal procedures performed from 2016 through June 2026 within a single-surgeon program sequence. The detailed procedural mix included 136 right colectomies, 83 left colectomies, 26 transverse or splenic-flexure resections, 116 rectal procedures, and 3 total colectomies. For statistical modelling, procedures were grouped as standard colon ($n = 219$), transverse/splenic flexure ($n = 26$), rectal ($n = 116$), and total colectomy ($n = 3$). The da Vinci Si platform was used in 269 procedures and the Xi platform in 95. Throughout the program, procedures followed standardized procedure-specific institutional workflows, including predefined trocar configurations, docking strategies, and operative sequences adapted to the anatomic target; these workflows were refined iteratively while maintaining consistent oncologic principles. Detailed technical descriptions of the principal procedure-specific approaches used within the program have been reported previously [18–23]. Sixty-one procedures included an associated operation; 16 were prespecified as major concomitant procedures because an additional major resection or multivisceral component materially increased procedural complexity.

Age and ASA class were available for all 364 procedures, as were operative duration, postoperative LOS, and major-morbidity status. The cohort partially overlaps with a previously published 320-procedure series from the same program [18]; that report addressed safety, oncologic reliability, and cost-effectiveness, whereas the present study evaluates a distinct longitudinal program-maturation hypothesis across the complete 364-procedure sequence.

Exposure: accumulated program experience

For each procedure, prior global robotic colorectal experience was defined as the number of qualifying program procedures completed before the index operation. The first procedure therefore had zero prior cases and the final procedure had 363. The exposure was transformed as $\log(1 + \text{prior experience})$, which reduces leverage from the later high-volume portion of the sequence and permits interpretation on a relative experience scale. Model coefficients were converted to percentage change, or odds ratio, per doubling of $(1 + \text{prior experience})$. Accumulated experience and calendar date were almost perfectly correlated in the definitive sequence (Spearman $\rho > 0.999$); both variables were therefore not entered simultaneously because their independent effects are not statistically identifiable. All coefficients are interpreted as longitudinal program-maturation associations rather than isolated causal effects of surgeon experience.

Outcomes and covariates

The principal clinical outcomes were postoperative LOS and major postoperative morbidity. LOS was recorded in postoperative days for the index admission and was available for all 364 procedures. Major morbidity was defined as any postoperative complication of Clavien-Dindo grade III or higher [24] and was ascertained for the entire cohort. Conversion to open surgery was analysed descriptively and was not incorporated into a composite endpoint.

Operative duration, recorded in minutes for each procedure, was the principal process/efficiency outcome and was analysed across the complete 364-case chronological sequence. Core adjustment variables were chosen a priori to account for major sources of case-mix and program heterogeneity: procedure family, robotic platform, associated-procedure status, age, and ASA class. Body mass index (BMI) was not included in the primary models because it was incompletely available and was therefore restricted to sensitivity analysis. The 16 major concomitant procedures were prespecified for exclusion in a sensitivity analysis, and a second sensitivity analysis excluded all procedures involving any associated operation.

Statistical analysis

Continuous outcomes were analysed on the logarithmic scale using multivariable ordinary least-squares models with HC3 heteroskedasticity-robust standard errors and finite-sample t inference. The primary

LOS model included $\log(1 + \text{prior global experience})$, procedure family, robotic platform, associated-procedure status, age, and ASA class. Prespecified sensitivity analyses used a Gamma generalized linear model with log link, excluded the 16 major concomitant procedures, excluded all procedures with any associated operation, and added BMI in the subset with available values. A process model additionally included $\log(\text{operative duration})$. Change in the experience coefficient after adding operative duration was interpreted as process-level associational attenuation only and not as formal causal mediation.

Operative duration was analysed with an analogous multivariable log-linear model with HC3 robust standard errors and finite-sample t inference across all 364 procedures. Sensitivity analyses excluded major concomitant procedures and then all associated procedures. Prespecified interaction terms tested whether the longitudinal experience slope differed by robotic platform or by associated-procedure status. Because the study objective concerned program-wide maturation rather than a discrete proficiency threshold, no post hoc breakpoint was selected and no CUSUM-derived case number was used as the primary exposure.

As an additional model-form sensitivity analysis, restricted cubic splines with four knots placed at the 5th, 35th, 65th, and 95th percentiles of $\log(1 + \text{prior experience})$ were fitted separately for LOS and operative duration using the same covariate adjustment as the corresponding primary models. HC3 robust finite-sample Wald tests assessed the overall experience association and departure from linearity on the log-experience scale. This analysis was intended to test the functional-form assumption of the primary models rather than to identify a new proficiency threshold. Major morbidity was not spline-modelled because only 15 events were available.

Major morbidity was analysed using Firth penalized logistic regression because only 15 events occurred [25, 26]. To preserve model parsimony in the sparse-event setting, ASA was entered as an ordinal term; the remaining adjustment structure paralleled the principal models. Continuous covariates were centred and scaled only for numerical stability, and the reported experience effect was transformed back to the original log-experience scale. Firth models were implemented with the `logistf` package version 1.26.1 and profile-likelihood 95% confidence intervals. Odds ratios are reported per doubling of $(1 + \text{prior experience})$. Safety sensitivities excluded major concomitant procedures and all associated procedures; in the latter subset, associated-procedure status was omitted because it was constant by definition. Sensitivity, interaction, and spline analyses were used to assess robustness or model form rather than to support independent confirmatory claims; no adjustment for multiple testing was therefore applied, and their p values were interpreted descriptively. Two-sided p values and 95% confidence intervals are reported. All analyses were performed in R version 4.6.1 (2026-06-24 ucrt) under Windows 11 x64. Reporting follows STROBE principles [27].

Ethics and consent

The local Institutional Review Board waived ethical review and approval because all data were fully anonymised and derived from standard clinical activity. No additional procedures or patient interventions

were performed beyond routine surgical care. Written informed consent for the surgical procedure and for the use of anonymised clinical data for research purposes was obtained from all patients during hospital admission.

Results

Program characteristics

The cohort comprised 364 robotic colorectal procedures. Standard colon procedures accounted for 219 cases (60.2%), rectal procedures for 116 (31.9%), transverse or splenic-flexure resections for 26 (7.1%), and total colectomy for 3 (0.8%). The Si platform was used in 269 cases (73.9%) and the Xi platform in 95 (26.1%). Mean age was 68.9 years and median age 70 years (IQR 61-78). ASA distribution was 86 ASA I, 145 ASA II, 119 ASA III, and 14 ASA IV. Median operative duration was 242.5 minutes (IQR 205-299), median LOS was 6 days (IQR 5-8), and LOS, operative duration, and major-morbidity status were available for the full cohort (Table 1).

Program maturation and postoperative recovery

In the primary adjusted log-LOS model, each doubling of (1 + prior global experience) was associated with 5.1% shorter LOS (95% CI 2.2%-7.9% shorter; $p < 0.001$; adjusted $R^2 = 0.113$). The estimate remained closely similar after excluding the 16 major concomitant procedures ($n = 348$; 4.9% shorter; 95% CI 2.0%-7.7%; $p = 0.001$) and after excluding every associated procedure ($n = 303$; 4.8% shorter; 95% CI 1.8%-7.7%; $p = 0.002$), indicating that the primary association was not driven by the most complex combined operations.

The Gamma log-link sensitivity produced a smaller and less precise estimate (3.1% shorter per doubling; 95% CI 7.8% shorter to 1.7% longer; $p = 0.201$), but the direction of association remained concordant with the primary model. In the BMI-adjusted subset ($n = 189$), the experience coefficient was markedly attenuated and imprecise (0.8% shorter; 95% CI 10.0% shorter to 9.4% longer; $p = 0.879$). Because BMI availability reduced the analytic sample substantially, this subset analysis was treated as a sensitivity analysis rather than a competing primary model.

When log(operative duration) was added to the primary LOS model, the experience association attenuated from 5.1% to 3.8% shorter LOS per doubling (95% CI 0.8%-6.7% shorter; $p = 0.014$). Operative duration remained associated with LOS after multivariable adjustment: each doubling of operative duration corresponded to 18.9% longer LOS (95% CI +3.8% to +36.2%; $p = 0.013$). Model fit increased from an adjusted R^2 of 0.113 in the primary model to 0.141 in the process model. This process-level attenuation is compatible with partial overlap between program efficiency and postoperative recovery, but it does not establish causal mediation (Table 2).

Program maturation and operative efficiency

Across all 364 procedures, the primary log-linear model yielded an average association of 5.3% shorter operative duration per doubling of (1 + prior experience) (95% CI 3.3%-7.4% shorter; $p < 0.001$; adjusted $R^2 = 0.175$). The estimate was highly stable after excluding the 16 major concomitant procedures ($n = 348$; 5.3% shorter; 95% CI 3.2%-7.4%; $p < 0.001$) and after excluding all associated procedures ($n = 303$; 4.8% shorter; 95% CI 2.7%-6.8%; $p < 0.001$). There was no statistical evidence that the longitudinal slope differed by robotic platform (interaction $p = 0.773$) or associated-procedure status (interaction $p = 0.854$); these null interaction tests should not be interpreted as proof of equivalence (Table 3).

In the restricted cubic spline sensitivity analysis (Online Resource 1), the overall experience association remained significant for LOS (robust Wald $p = 0.004$), with no evidence of departure from the primary linear log-experience form (non-linearity $p = 0.621$; Fig. 1). For operative duration, the overall experience association remained strong ($p < 0.001$), but there was clear evidence of non-linearity ($p < 0.001$; Fig. 2). Accordingly, the primary 5.3% per-doubling estimate should be interpreted as an average log-linear summary across the full program sequence rather than as a constant effect at every experience level (Online Resource 1, Table S1).

Major morbidity and conversion

Major postoperative morbidity occurred in 15/364 procedures (4.1%). In the adjusted Firth penalized logistic model, the odds ratio for major morbidity per doubling of (1 + prior experience) was 1.48 (95% profile-likelihood CI 0.84-3.64; $p = 0.208$). Excluding major concomitant procedures yielded OR 1.46 (95% CI 0.84-3.62; $p = 0.218$), while excluding all associated procedures yielded OR 1.51 (95% CI 0.87-3.78; $p = 0.165$). All three Firth models converged. The point estimates were above unity, but the confidence intervals were wide and crossed 1 substantially. With only 15 major events, these data did not support a statistically precise longitudinal safety trend and should not be interpreted as evidence of either improvement or deterioration in major morbidity. Conversion to open surgery occurred in 6/364 procedures (1.6%) (Table 4).

Discussion

This study evaluated maturation of a heterogeneous robotic colorectal program across three deliberately distinct domains: postoperative recovery, operative efficiency, and severe morbidity. The principal finding was a consistent longitudinal association between accumulated program experience and shorter LOS, together with a strong overall association with shorter operative duration. The spline sensitivity analysis refined the latter finding by showing that the operative-duration trajectory was non-linear rather than characterized by a single constant slope. By contrast, major morbidity was uncommon overall and the small number of events did not support a precise longitudinal safety slope. The measurable maturation

signals therefore resided primarily in recovery and process efficiency, while safety was characterized by a low overall event rate and wide uncertainty rather than by a demonstrable monotonic trend.

The findings differ conceptually from conventional learning-curve studies that seek a case number at which proficiency is reached. A recent review of robotic colorectal CUSUM studies found first inflection points ranging from 3 to 110 cases and showed that apparent inflection location was itself associated with study size [1]. Earlier program-level work by Guend et al. distinguished institutional from individual learning in 418 robotic colorectal cancer resections and suggested that institutional maturation extends beyond a single surgeon's acquisition of proficiency [28]. Procedure-specific studies likewise report different trajectories for colon and rectal resections and show that safety curves need not mirror time-based curves [4–10, 29, 30]. These observations illustrate why a single threshold can be useful for training or credentialing yet remain an unstable descriptor of a mature, heterogeneous service. By modelling accumulated experience continuously, the present study addresses a different question: whether clinically relevant outcomes continue to change across the full program sequence rather than where an arbitrarily defined learning phase ends. The spline sensitivity result for operative duration further shows that program evolution need not follow a single constant slope.

The LOS association is clinically relevant because it links program maturation to a patient-centered recovery metric rather than to operating-room efficiency alone. Higher robotic colorectal volume has previously been associated with shorter LOS and lower conversion rates [13], while contemporary real-world adoption studies have reported changes in LOS and operative performance across institutional robotic implementation phases and platforms [14, 15]. Lin et al. described distinct surgeon and teamwork maturation during robotic colorectal surgery integrated with an enhanced-recovery program [12]. These observations support the premise that postoperative recovery reflects more than console skill. LOS is also sensitive to enhanced-recovery pathways, discharge practice, complications, social factors, and institutional organization [16]; our result should therefore be interpreted as a program-level longitudinal association rather than evidence that technical experience alone shortened hospitalization.

Operative duration showed a strong but non-linear maturation signal. The primary log-linear model summarized the full sequence as an approximately 5% shorter duration per doubling of experience, and this average estimate changed little when major concomitant or all associated procedures were excluded, consistent with the direction reported in recent single-surgeon, educational, and platform-transition series [4, 15, 29]. However, restricted cubic splines showed significant departure from a constant log-linear slope, indicating that efficiency gains were not uniform across the program sequence. This is compatible with a maturation process shaped by changing case mix, platform, team organization, and technical standardization rather than a simple monotonic learning law. Importantly, the experience-by-platform interaction was not significant, so there was no statistical evidence that the overall longitudinal decline was confined to one robotic platform. This does not establish platform equivalence: platform transition occurred within the chronological program and therefore cannot be disentangled from contemporaneous changes in team familiarity, case selection, or perioperative organization.

The process model provides a useful but deliberately cautious layer of interpretation. Operative duration remained associated with LOS after multivariable adjustment, and adding it to the LOS model attenuated the experience coefficient from 5.1% to 3.8% per doubling. This process-level attenuation is consistent with a potential contribution of increasing technical and organizational efficiency to postoperative recovery, but it is not a mediation analysis and does not establish an indirect causal pathway. Operative duration is simultaneously a marker of technical complexity, adhesiolysis, multivisceral work, anesthetic exposure, intraoperative events, and team performance; stronger temporal and causal assumptions would be required to interpret it as a mediator.

Safety must be interpreted differently from efficiency. Major morbidity was 4.1%, broadly comparable with low severe-complication rates reported in structured robotic colorectal series [4–6]. With only 15 events, however, even Firth penalized logistic regression with profile-likelihood confidence intervals yielded substantial uncertainty. The adjusted point estimate above unity should not be described as a worsening trend because it was statistically compatible with lower risk, no association, or higher risk. In addition, severe postoperative complications may reflect patient characteristics, disease severity, procedural complexity, intraoperative events, perioperative management, and other unmeasured or time-varying factors not fully captured by the adjustment set; residual confounding therefore further limits attribution of the observed morbidity pattern to accumulated program experience. The defensible conclusion is narrower: major morbidity was uncommon overall, but sparse events did not permit a precise longitudinal estimate. This distinction also avoids treating a non-significant safety coefficient as evidence of equivalence or noninferiority.

The term program maturation is therefore more appropriate than surgeon learning for the exposure analyzed here. Structured robotic services evolve through standardized operative steps, bedside and theatre-team familiarity, perioperative care, platform transitions, and changes in case selection [11, 12, 15, 19–23, 31]. In our sequence, accumulated experience and calendar time were essentially collinear, making their independent contributions non-identifiable. The experience coefficient should consequently be read as a compact measure of longitudinal program development rather than an isolated effect of repeated console exposure. This limits causal attribution but also reflects the clinical reality that mature surgical programs evolve through interacting technical and organizational processes.

Strengths and limitations

A principal strength is the use of a complete consecutive 364-procedure sequence with complete LOS, operative-duration, age, ASA, and major-morbidity data, allowing the same exposure to be examined across complementary clinical and process domains. The continuous exposure avoids data-driven breakpoint selection, while prespecified exclusions test whether the principal associations were driven by combined or more complex procedures. The single-surgeon sequence reduces inter-operator heterogeneity, although it necessarily limits external generalizability. The spline sensitivity analysis provides an additional model-form check rather than assuming that the experience association must follow a constant slope. The all-procedure sequence spans several colorectal procedure families and

two robotic platforms; this heterogeneity is a strength for a program-level maturation question because it reflects the evolving case mix of a real-world robotic colorectal service.

The study remains retrospective, single-center, and based on a single-surgeon program, limiting generalizability to centers with different baseline minimally invasive expertise, staffing, referral patterns, and perioperative pathways. The same procedural heterogeneity that supports program-level inference limits procedure-specific interpretation and precludes assigning the observed longitudinal slope to any one operation type. Near-perfect correlation between accumulated experience and calendar time prevents separation of technical learning from contemporaneous changes in team organization, enhanced recovery practice, platform, and case selection; residual confounding by disease complexity and other time-varying factors is therefore unavoidable. The LOS association was robust to the prespecified case-exclusion sensitivities and showed no evidence of non-linear functional form in the spline analysis, but it was smaller and less precise under the Gamma log-link specification and markedly attenuated in the incomplete BMI-adjusted subset. These sensitivities temper the strength of inference for LOS relative to the more consistent operative-duration signal. For operative duration, significant spline non-linearity means that the reported 5.3% change per doubling should be understood as an average log-linear summary across the program rather than a literal constant effect at all experience levels. Adjusted R^2 values were modest, consistent with substantial residual variability in both recovery and operative duration. Major morbidity was sparse, yielding wide uncertainty despite bias-reduced modelling, and may also be influenced by unmeasured patient-, disease-, procedure-, and perioperative factors. Finally, LOS is a composite recovery measure influenced by both clinical condition and institutional discharge processes.

Conclusions

Across 364 consecutive robotic colorectal procedures, increasing cumulative program experience was associated, after multivariable adjustment, with shorter postoperative LOS and shorter operative duration. Spline sensitivity analysis supported the primary log-linear form for LOS but showed that the operative-duration trajectory was non-linear, indicating that efficiency gains were not constant across the full program sequence. The LOS association was attenuated after operative duration was included, consistent with a potential process-level contribution of increasing technical and organizational efficiency to recovery, although causal mediation cannot be inferred. Major morbidity was uncommon overall; with only 15 severe events, the longitudinal estimate remained imprecise, while residual confounding limited attribution of the observed pattern to accumulated program experience. Because experience and calendar time were almost perfectly collinear, these findings reflect longitudinal program maturation rather than an isolated causal surgeon-experience effect. Taken together, the results support a multidimensional concept of robotic program maturation encompassing recovery and operative efficiency alongside a low overall rate of major morbidity rather than a single procedure-specific operative-time threshold.

Declarations

Funding: The authors declare that no funds, grants, or other support were received for this study.

Competing interests: The authors have no relevant financial or non-financial interests to disclose.

Author contributions (CRediT taxonomy): Igor Monsellato: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing - original draft, Writing - review & editing, Supervision, Project administration. Marco Palucci: Investigation, Data curation, Validation, Writing - review & editing. Fabio Giannone: Investigation, Data curation, Validation, Writing - review & editing. Fabiana Marotta: Investigation, Data curation, Writing - review & editing. Mariantonietta Alagia: Investigation, Data curation, Writing - review & editing. Marco Lodin: Investigation, Data curation, Validation, Writing - review & editing. Gianluca Cassese: Methodology, Validation, Writing - review & editing, Supervision. All authors read and approved the final manuscript.

Ethics approval: The local Institutional Review Board waived ethical review and approval because all data were fully anonymised and derived from standard clinical activity. No additional procedures or patient interventions were performed beyond routine surgical care.

Consent to participate: Written informed consent for the surgical procedure and for the use of anonymised clinical data for research purposes was obtained from all patients during hospital admission.

Consent to publish: Not applicable; no identifiable individual patient information is presented.

Data availability: De-identified analytical data may be made available on reasonable request subject to institutional, ethical, and privacy requirements.

Code availability: The reproducible R code supporting the primary and sensitivity analyses is available from the corresponding author on reasonable request.

References

1. Pal A, Jayawardene M (2026) Robotic colorectal surgery: making sense of the learning curve. *J Robot Surg* 20:309. <https://doi.org/10.1007/s11701-026-03252-5>
2. Flynn J, Larach JT, Kong JCH, Waters PS, Warriar SK, Heriot A (2021) The learning curve in robotic colorectal surgery compared with laparoscopic colorectal surgery: a systematic review. *Colorectal Dis* 23:2806–2820. <https://doi.org/10.1111/codi.15843>
3. Wong SW, Crowe P (2022) Factors affecting the learning curve in robotic colorectal surgery. *J Robot Surg* 16:1249–1256. <https://doi.org/10.1007/s11701-022-01373-1>
4. Madarasz Z, Nowakowski K, Leitz M et al (2026) Learning curves and outcomes of robotic colorectal surgery: a single-surgeon experience within a structured dual-console training program. *J*

- Robot Surg 20:170. <https://doi.org/10.1007/s11701-025-03139-x>
5. Arquilliere J, Dubois A, Rullier E et al (2023) Learning curve for robotic-assisted total mesorectal excision: a multicentre, prospective study. *Colorectal Dis* 25:1863–1877. <https://doi.org/10.1111/codi.16695>
 6. Burghgraef TA, Sikkenk DJ, Crolla RMPH et al (2023) Assessing the learning curve of robot-assisted total mesorectal excision: a multicenter study considering procedural safety, pathological safety, and efficiency. *Int J Colorectal Dis* 38:9. <https://doi.org/10.1007/s00384-022-04303-7>
 7. Tang B, Li T, Gao G, Shi J, Li T (2022) Learning curve of robotic-assisted total mesorectal excision for rectal cancer. *Front Oncol* 12:931426. <https://doi.org/10.3389/fonc.2022.931426>
 8. Odermatt M, Ahmed J, Panteleimonitis S, Khan J, Parvaiz A (2017) Prior experience in laparoscopic rectal surgery can minimise the learning curve for robotic rectal resections: a cumulative sum analysis. *Surg Endosc* 31:4067–4076. <https://doi.org/10.1007/s00464-017-5453-9>
 9. Parisi A, Scrucca L, Desiderio J et al (2017) Robotic right hemicolectomy: analysis of 108 consecutive procedures and multidimensional assessment of the learning curve. *Surg Oncol* 26:28–36. <https://doi.org/10.1016/j.suronc.2016.12.005>
 10. Bhattacharya A, Bhattacharyya S, Das P (2025) Learning curve in robotic colorectal surgery. *JSLs* 29. <https://doi.org/10.4293/JSLs.2025.00077>. e2025.00077
 11. Thomas A, Altaf K, Sochorova D, Gur U, Parvaiz A, Ahmed S (2021) Effective implementation and adaptation of structured robotic colorectal program in a busy tertiary unit. *J Robot Surg* 15:731–739. <https://doi.org/10.1007/s11701-020-01169-1>
 12. Lin CY, Liu YC, Chen MC, Chiang FF (2022) Learning curve and surgical outcome of robotic assisted colorectal surgery with ERAS program. *Sci Rep* 12:20566. <https://doi.org/10.1038/s41598-022-24665-w>
 13. Bastawrous A, Baer C, Rashidi L, Neighorn C (2018) Higher robotic colorectal surgery volume improves outcomes. *Am J Surg* 215:874–878. <https://doi.org/10.1016/j.amjsurg.2018.01.042>
 14. Massias S, Pajaziti Q, Rad AA et al (2026) Comparative outcomes of laparoscopic and robotic colorectal cancer surgery in the NHS: real-world evidence from sequential adoption of Versius and da Vinci Xi. *J Robot Surg* 20:240. <https://doi.org/10.1007/s11701-026-03186-y>
 15. Nahime RH, Stevanato Filho PR, Bezerra TS et al (2026) Impact of robotic platform transition on short term outcomes in colorectal cancer surgeries. *J Robot Surg* 20:905. <https://doi.org/10.1007/s11701-026-03855-y>
 16. Gustafsson UO, Scott MJ, Hubner M et al (2019) Guidelines for perioperative care in elective colorectal surgery: Enhanced Recovery After Surgery (ERAS) Society recommendations: 2018. *World J Surg* 43:659–695. <https://doi.org/10.1007/s00268-018-4844-y>
 17. Gustafsson UO, Rockall TA, Wexner S et al (2025) Guidelines for perioperative care in elective colorectal surgery: Enhanced Recovery After Surgery (ERAS) Society recommendations 2025. *Surgery* 184:109397. <https://doi.org/10.1016/j.surg.2025.109397>

18. Monsellato I, Gatto T, Lodin M et al (2025) Long-term single-surgeon outcomes of 320 robotic colorectal cancer resections: safety, oncologic reliability, and cost-effectiveness. *Int J Med Robot* 21:e70126. <https://doi.org/10.1002/rcs.70126>
19. Monsellato I, Gatto T, Lodin M, Panaro F (2025) Robotic CME in 110 consecutive cases: feasibility and short-term technical and oncological outcomes. *Minerva Surg* 80:7–14. <https://doi.org/10.23736/S2724-5691.24.10319-X>
20. Monsellato I, Gatto T, Palucci M et al (2025) Optimized 'Full Right' instrument configuration in robotic rectal surgery with the Da Vinci Xi system: a prospective single-center experience. *Surg Innov* 32:495–501. <https://doi.org/10.1177/15533506251374470>
21. Monsellato I, Gatto T, Lodin M et al (2024) Robotic splenic flexure cancer resection: technique and short-term outcomes. *Minerva Surg* 79:607–615. <https://doi.org/10.23736/S2724-5691.24.10477-7>
22. Monsellato I, Gatto T, Palucci M et al (2025) Robotic selective left colectomy with inferior mesenteric artery and inferior mesenteric vein preservation: a stepwise video technique. *Ann Coloproctol* 41:354–356. <https://doi.org/10.3393/ac.2025.00682.0097>
23. Monsellato I, Gatto T, Alagia MA et al (2025) Fully robotic total colectomy in high-risk patients and review of literature. *Int J Med Robot* 21:e70098. <https://doi.org/10.1002/rcs.70098>
24. Dindo D, Demartines N, Clavien PA (2004) Classification of surgical complications: a new proposal with evaluation in a cohort of 6336 patients and results of a survey. *Ann Surg* 240:205–213. <https://doi.org/10.1097/01.sla.0000133083.54934.ae>
25. Firth D (1993) Bias reduction of maximum likelihood estimates. *Biometrika* 80:27–38. <https://doi.org/10.1093/biomet/80.1.27>
26. Kosmidis I, Firth D (2021) Jeffreys-prior penalty, finiteness and shrinkage in binomial-response generalized linear models. *Biometrika* 108:71–82. <https://doi.org/10.1093/biomet/asaa052>
27. von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP, STROBE Initiative (2007) The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. *Lancet* 370:1453–1457. [https://doi.org/10.1016/S0140-6736\(07\)61602-X](https://doi.org/10.1016/S0140-6736(07)61602-X)
28. Guend H, Widmar M, Patel S et al (2017) Developing a robotic colorectal cancer surgery program: understanding institutional and individual learning curves. *Surg Endosc* 31:2820–2828. <https://doi.org/10.1007/s00464-016-5292-0>
29. Yabusaki N, Ishiyama A, Mori T, Hirota M, Yokoi K (2026) Risk-adjusted learning curve for robotic colorectal surgery in an educational setting: a single-center consecutive series. *J Robot Surg* 20:326. <https://doi.org/10.1007/s11701-026-03292-x>
30. Nasser Y, Stettler I, Shen W et al (2021) Learning curve in robotic colorectal surgery. *J Robot Surg* 15:489–495. <https://doi.org/10.1007/s11701-020-01131-1>
31. Van Eetvelde E, Duhoky R, Piozzi GN et al (2025) European multicentre analysis of the implementation of robotic complete mesocolic excision for right-sided colon tumours. *Colorectal Dis* 27:e17287. <https://doi.org/10.1111/codi.17287>

Tables

Table 1. Program composition and principal outcomes

Characteristic	Value
Total procedures	364
Right colectomy	136 (37.4%)
Left colectomy	83 (22.8%)
Transverse/splenic-flexure resection	26 (7.1%)
Rectal procedure	116 (31.9%)
Total colectomy	3 (0.8%)
da Vinci Si / Xi	269 (73.9%) / 95 (26.1%)
Associated procedures	61 (16.8%)
Major concomitant procedures	16 (4.4%)
ASA I / II / III / IV	86 / 145 / 119 / 14
Age	Mean 68.9 years; median 70 (IQR 61-78)
Operative duration	242.5 min (IQR 205–299); n=364
Postoperative LOS	6 days (IQR 5–8); n=364
Major morbidity (CD >=III)	15/364 (4.1%)
Conversion to open surgery	6/364 (1.6%)

Table 2. Adjusted longitudinal models for postoperative length of stay

Analysis	N	Effect estimate	95% CI	p
Primary log-LOS HC3	364	-5.1%	-7.9% to -2.2%	<0.001
Primary + log operative duration	364	-3.8%	-6.7% to -0.8%	0.014
Operative-duration term in process model	364	+18.9%	+3.8% to +36.2%	0.013
Exclude 16 major concomitant procedures	348	-4.9%	-7.7% to -2.0%	0.001
Exclude all associated procedures	303	-4.8%	-7.7% to -1.8%	0.002
Gamma log-link sensitivity	364	-3.1%	-7.8% to +1.7%	0.201
BMI-adjusted sensitivity	189	-0.8%	-10.0% to +9.4%	0.879

Except for the operative-duration term in the process model, effects are expressed as percentage change in LOS per doubling of (1 + prior global experience); negative values indicate shorter LOS. For the operative-duration term, +18.9% represents the percentage change in LOS per doubling of operative duration. Core models adjusted for procedure family, robotic platform, associated procedure, age, and ASA class. Adjusted R² was 0.1134 for the primary log-LOS model and 0.1412 for the process model including operative duration.

Table 3. Adjusted longitudinal models for operative duration

Analysis	N	Effect per doubling	95% CI	p
Primary full sequence	364	-5.3%	-7.4% to -3.3%	<0.001
Exclude 16 major concomitant procedures	348	-5.3%	-7.4% to -3.2%	<0.001
Exclude all associated procedures	303	-4.8%	-6.8% to -2.7%	<0.001

All operative-duration models used HC3 robust standard errors with finite-sample t inference and adjusted for procedure family, platform, associated procedure where applicable, age, and ASA class. Adjusted R² for the primary full-sequence model was 0.175. Prespecified slope-heterogeneity tests showed no detectable interaction with robotic platform (p=0.773) or associated-procedure status (p=0.854); these null tests do not establish equivalence.

Table 4. Firth penalized logistic models for major morbidity

Analysis	N / events	OR per doubling	95% CI	p
Full cohort	364 / 15	1.48	0.84-3.64	0.208
Exclude 16 major concomitant procedures	348 / 14	1.46	0.84-3.62	0.218
Exclude all associated procedures	303 / 10	1.51	0.87-3.78	0.165

Odds ratios are reported per doubling of (1 + prior global experience). ASA was entered as an ordinal term. Profile-likelihood 95% confidence intervals are shown. All three Firth models converged. In the sensitivity analysis excluding all associated procedures, associated-procedure status was omitted because it was constant by definition.

Figures

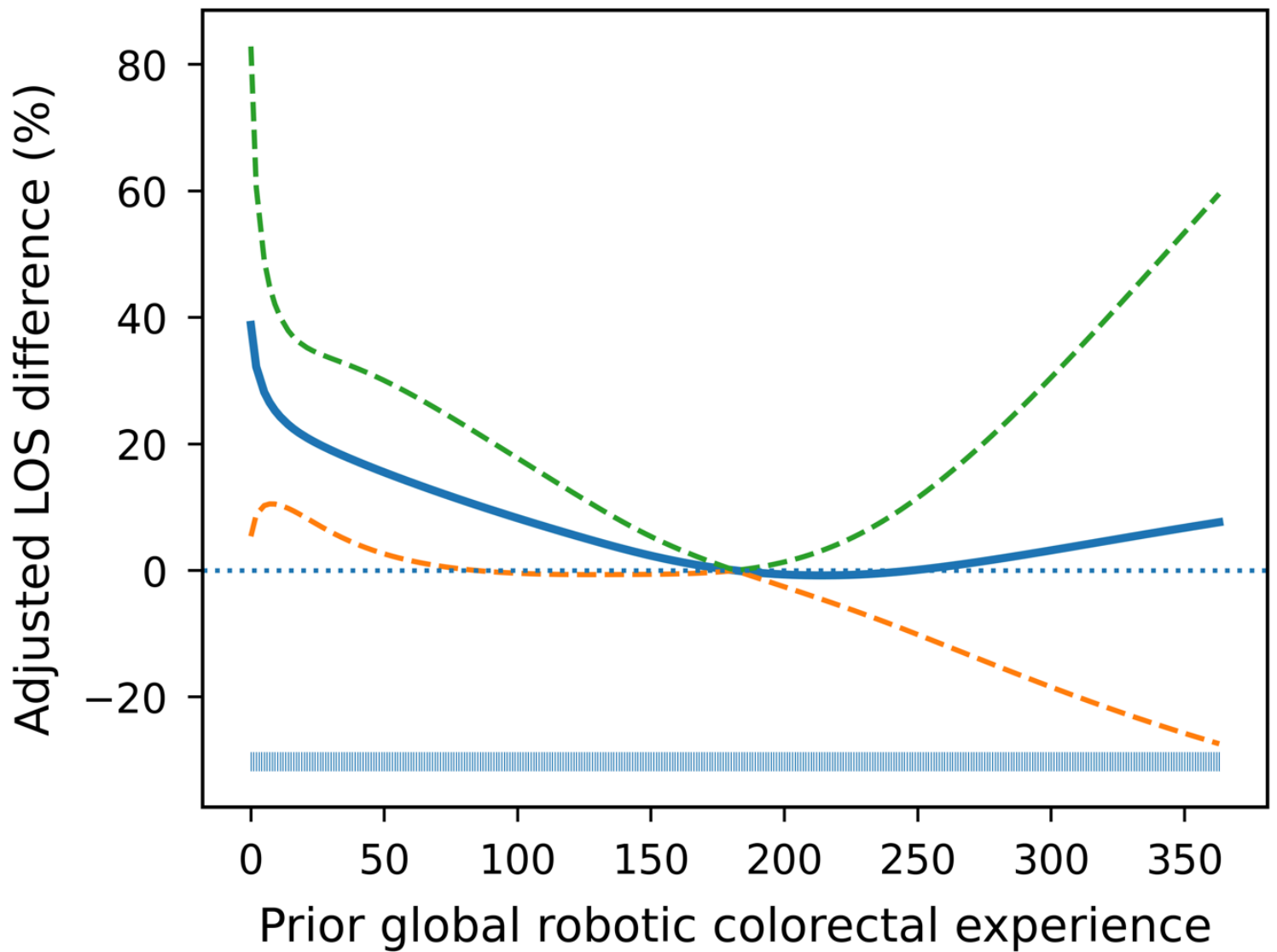


Figure 1

Adjusted restricted cubic spline association between prior global robotic colorectal experience and postoperative length of stay. The solid line shows the adjusted percentage difference relative to median prior experience; dashed lines show 95% confidence intervals. The model adjusted for procedure family, robotic platform, associated-procedure status, age, and ASA class. Overall RCS association $p=0.004$; non-linearity $p=0.621$

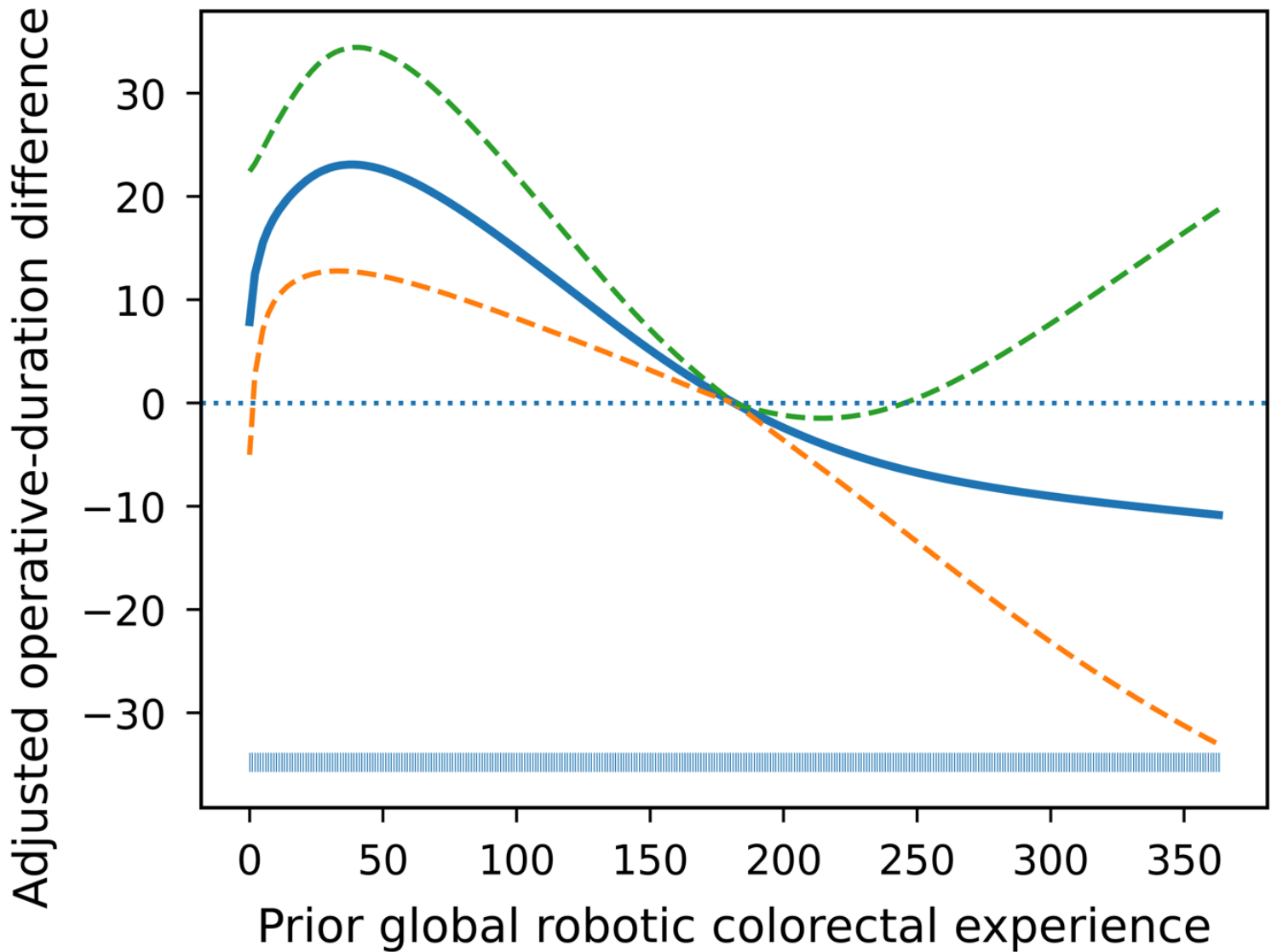


Figure 2

Adjusted restricted cubic spline association between prior global robotic colorectal experience and operative duration. The solid line shows the adjusted percentage difference relative to median prior experience; dashed lines show 95% confidence intervals. The model adjusted for procedure family, robotic platform, associated-procedure status, age, and ASA class. Overall RCS association $p < 0.001$; non-linearity $p < 0.001$

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [ESM1.pdf](#)