

Online Resource 1 • Supplementary sensitivity analysis

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

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Purpose. To test whether the primary log-linear specification of cumulative programme experience adequately represented the functional form of its association with postoperative length of stay (LOS) and operative duration.

Supplementary methods

Restricted cubic spline analysis. The exposure was $\log(1 + \text{prior global robotic colorectal experience})$, matching the primary manuscript models. Restricted cubic splines with four knots at the 5th, 35th, 65th, and 95th percentiles of the transformed exposure were fitted separately for $\log(\text{LOS})$ and $\log(\text{operative duration})$. The corresponding prior-experience locations were approximately 18.1, 127.0, 235.9, and 344.8 prior procedures. Models used the same adjustment set as the primary continuous-outcome analyses: procedure family, robotic platform, associated-procedure status, age, and ASA class. HC3 heteroskedasticity-robust covariance estimates and finite-sample Wald F tests were used. One Wald test assessed the overall experience association; a second tested the nonlinear spline terms jointly, thereby assessing departure from the primary linear relationship on the log-experience scale.

Safety endpoint. Major morbidity was not spline-modelled because only 15 events occurred, making a flexible nonlinear binary-outcome model vulnerable to overfitting and unstable inference. The Firth penalized logistic model reported in the main manuscript therefore remains the safety analysis.

Calendar time. No separate calendar-year or calendar-era effect estimate is included in this supplementary report because accumulated experience and calendar time are essentially collinear in the longitudinal programme sequence. The rank-correlation checkpoint (Spearman $\rho > 0.999$) is retained only to support the manuscript statement that their independent contributions are not statistically identifiable; the supplementary analysis is restricted to testing the functional form of cumulative experience.

Supplementary results

Primary-model sanity check. Re-running the primary linear models in R 4.6.1 reproduced the definitive manuscript estimates: LOS -5.12% per doubling (95% CI -7.93% to -2.24% ; $p < 0.001$; adjusted $R^2 = 0.113$) and operative duration -5.34% per doubling (95% CI -7.37% to -3.27% ; $p < 0.001$; adjusted $R^2 = 0.175$).

Spline findings. For LOS, the overall experience association remained significant, whereas the nonlinear terms were not significant. This supports the primary log-linear functional form as an adequate summary of the LOS association. For operative duration, both the overall association and the nonlinear terms were significant, demonstrating that the longitudinal efficiency trajectory departs from a single constant log-linear slope. The primary 5.3% per-doubling estimate is therefore best interpreted as an average summary across the complete sequence, not as a constant effect at every experience level.

Supplementary Table S1. Restricted cubic spline robust Wald tests

Outcome	Test	df1	df2	F	p
LOS	Overall experience association (RCS)	3	351	4.527	0.004
LOS	Nonlinearity beyond linear log-experience	2	351	0.478	0.621
Operative duration	Overall experience association (RCS)	3	351	15.773	<0.001
Operative duration	Nonlinearity beyond linear log-experience	2	351	9.755	<0.001

RCS, restricted cubic spline. The nonlinearity test jointly evaluates the two nonlinear spline terms. All models adjusted for procedure family, robotic platform, associated-procedure status, age, and ASA class and used HC3 robust finite-sample inference.

Supplementary Table S2. Restricted cubic spline knot locations

Percentile	Knot on $\log(1 + \text{experience})$ scale	Equivalent prior experience
5th	2.952	18.1
35th	4.852	127.0
65th	5.468	235.9
95th	5.846	344.8

Interpretive note

The supplementary analysis does not identify or propose a new proficiency threshold. Its role is diagnostic: it tests whether the chosen continuous exposure specification is adequate. The absence of detectable LOS nonlinearity supports the primary log-linear LOS model. The operative-duration nonlinearity indicates that programme efficiency evolved unevenly across the sequence, consistent with a multidimensional programme-maturation framework rather than a single universal learning slope.

Software

R version 4.6.1 (2026-06-24 ucrt), Windows 11 x64; sandwich version 3.1-3; readxl version 1.5.0.