The Death of Laparoscopy - Volume 2: A Revised Prognosis. A retrospective study

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The Death of Laparoscopy - Volume 2: A Revised Prognosis. A retrospective study.

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Abstract

Objective: To assess trends in surgical approaches (robotic, laparoscopic, and open) for various procedures, including prostatectomy, nephrectomy, cystectomy, colectomy, proctectomy, pancreatectomy, hepatectomy, and esophagectomy, and predict the future of these surgical approaches.

Summary Background Data: The rapid adoption of robotic surgery has raised critical questions about the future of traditional laparoscopic techniques. Understanding the trends and potential dominance of robotic surgery is essential for surgical training, healthcare infrastructure, and resource allocation.

Methods: This retrospective observational study utilized data from the American College of Surgeons National Surgical Quality Improvement Program (ACS-NSQIP) from 2012 to 2023. Vector Autoregressive modeling analyzed trends and predicted future patterns for robotic, laparoscopic, or open surgical approaches across the specified procedures. The study included all reported cases in the database where the surgical approach was specified.

Results: The analysis revealed a continued shift towards robotic surgery, particularly dominant in urologic procedures and rapidly adopted for complex operations like hepatectomy and esophagectomy. Laparoscopy's use is declining across most specialties, though it remains significant in colectomy. Open surgery persists at high rates, especially in pancreatic and rectal operations. Projections suggest robotic surgery will surpass laparoscopy in colectomy (44.5%) and proctectomy (38.3%) by 2026.

Conclusions: The transition toward robotic surgery continues across specialties at varying rates. These findings have significant implications for surgical training, healthcare infrastructure, and resource allocation. The high rates of open surgery in certain procedures highlight opportunities for broader adoption of minimally invasive techniques.

INTRODUCTION

The surgical field has undergone a dramatic transformation with the rapid rise of robotic surgery. Since its emergence in the early 2000s, this technology has experienced explosive growth, revolutionizing operating rooms and captivating surgeons and researchers (1-6). This surge in adoption is reflected in the expanding body of literature exploring its applications, outcomes, and broader implications (7, 8). Surgeons are increasingly drawn to the potential advantages of robotic platforms over traditional laparoscopy, including enhanced dexterity and precision through improved ergonomics and instrument control, superior 3D-enhanced visualization, and exciting possibilities of integration with artificial intelligence and the development of telesurgery (9-12). These advancements promise improved patient outcomes, shorter surgical learning curves, and expanded access to complex procedures.

This shift towards robotic surgery represents a significant paradigm shift, prompting questions about the long-term viability of traditional laparoscopic approaches. Recognizing this transformative trend, we initiated a novel study last year using Vector Autoregressive modeling to assess robotic surgery adoption patterns in the United States and predict its potential to eclipse laparoscopy across various surgical procedures and specialties (13). Our initial analysis, using data from the American College of Surgeons National Surgical Quality Improvement Program (ACS-NSQIP), pointed towards a striking trend: a rapid and widespread transition to robotic dominance in most procedures within the database.

With nearly two years of additional ACS-NSQIP data, we have revisited our analysis. This follow-up study aims not only to incorporate more recent data but, more critically, to address the gap in understanding whether the initial rapid rise of robotic surgery and the projected decline of laparoscopy—as forecasted in our prior work—have maintained their trajectory, accelerated, or decelerated in the face of evolving real-world practice. This update allows for a more robust validation of our Vector Autoregressive modeling approach in this dynamic context and provides more current, refined forecasts. Such updated predictions are crucial for timely decision-making in surgical training and resource allocation, given the swift pace of technological adoption. This updated analysis therefore allows us to more confidently address the central question: is laparoscopy facing inevitable decline, and how must surgeons adapt to this evolving surgical landscape?

METHODS

Study Design and Data Source

This study extends our previous analysis of surgical approach trends while incorporating methodological refinement and additional data (13). As with our initial investigation, we conducted this retrospective analysis following approval from our Institutional Review Board and adhered to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) Statement guidelines for observational studies (14).

The study utilized data from the ACS-NSQIP, a validated clinical database established in 1994 that collects risk-adjusted surgical outcomes data from participating hospitals. The database comprises a systematic sample of approximately 20% of all cases from participating institutions, with data collected by trained clinical reviewers.

Data Collection and Processing

Our analysis encompassed all elective surgical procedures in the ACS-NSQIP database where the surgical approach was specified. While our previous study analyzed data from 2012 through Q2 2021, the current investigation extended through 2023. To address the missing data in Q3 and

Q4 2021, we employed linear interpolation, a mathematical technique that estimates intermediate values by assuming a linear relationship between known data points. This method was chosen for its effectiveness in time series analysis and its ability to preserve trend consistency.

Classification of Surgical Approaches

A significant methodological adaptation was necessitated by changes in the ACS-NSQIP database structure beginning in 2022. Before 2022, surgical approaches were recorded in the targeted database using mutually exclusive categories. However, the 2022-2023 datasets incorporated surgical approach data in the general database with a more complex structure, allowing multiple approaches to be recorded for a single procedure.

In the 2022-2023 data, robotic procedures were identifiable by the presence of "Robot Used = Yes" and the inclusion of the laparoscopic approach in the operative approach variable, reflecting the technical requirement that robotic surgery utilizes laparoscopic access. To maintain methodological consistency while accommodating this structural change, we established the following classification system:

Cases were first evaluated for the presence of any laparoscopic approach in the operative approach variable. Among these laparoscopic cases, those marked as "Robot Used = Yes" were classified into the Robotic Surgery Group, while the remaining laparoscopic cases were assigned to the Laparoscopic Surgery Group. All other cases were classified into the Open Surgery Group, including the open approach with any combination of non-laparoscopic approaches (such as endoscopic, arthroscopic, or percutaneous techniques). In case of minimally invasive cases converted to open surgery, these cases were considered as minimally invesive (either laparoscopic or robotic), on an intention-to-treat basis.

This classification system preserved the essential relationships between surgical approaches while adapting to the more detailed documentation structure of the 2022-2023 data, ensuring consistency with our previous analytical framework.

Statistical Analysis

Consistent with the previous analysis in (13), the temporal relationships between surgical approaches were examined using Vector Autoregressive (VAR) models, which enable the study of dynamic interactions between multiple time series. These models extend the univariate autoregressive framework by incorporating multiple dependent variables, enabling analysis of their interdependencies and interactions over time (15). The analysis was performed using R version 4.3.0 with "tseries", "vars" , "funtimes", "urca" packages.

Model Selection and Validation

The appropriate lag order for the VAR models was determined through sequential testing procedures and model selection criteria, including the Akaike Information Criterion, Bayesian Information Criterion, and Hannan-Quinn criterion. Stationarity was assessed using the Augmented Dickey-Fuller test, and the presence of long-term relationships was examined using the Johansen co-integration test (16). Diagnostic tests for autocorrelation and heteroscedasticity in the residuals were performed to assess model fit.

Forecasting

Using the estimated VAR models, we generated forecasts of surgical approach trends through 2026, accompanied by 95% confidence intervals. These predictions incorporate the historical trends from our original analysis and the additional data through 2023, providing an updated perspective on the evolution of surgical techniques.

RESULTS

Urology

Analysis through Q4 2023 shows that in prostatectomy (**Figure 1a**), robotic surgery increased from 83.1% in Q2 2021 to 90.4% by Q4 2023, while open and laparoscopic approaches decreased to 7.8% and 1.8% from 10.6% and 6.2%, respectively. In nephrectomy (**Figure 1b**), robotic surgery utilization expanded from 55.1% to 61.2%, as laparoscopic approaches declined from 26.1% to 20.5% and open surgery decreased from 18.8% to 18.2%. For cystectomy (**Figure 1c**), robotic surgery increased from 26.3% to 42.8%, open surgery decreased from 72.5% to 56.0%, and laparoscopic approaches remained stable at approximately 1.2%.

Colectomy

Our previous analysis through Q2 2021 reported laparoscopic surgery at 50.5%, open surgery at 31.5%, and robotic surgery at 18.0%. We had predicted that robotic surgery would become the predominant approach by 2024, reaching 45.7% (95% CI 39.9-51.5%) by 2025. The data through 2023 (**Figure 2a**) showed that while robotic surgery continued to increase, reaching 24.3% by Q4 2023, it did not surpass laparoscopic surgery, which decreased to 43.5%, or open surgery, which persisted to 32.3% of cases. Our updated Vector Autoregressive model (**Figure 2b**), incorporating this additional data, now forecasts that by Q4 2026, robotic surgery will account for 44.5% (95% CI 32.8-56.3%) of colectomies, surpassing laparoscopic surgery and open surgery, expected to decrease at 25.8% (95% CI 3.5-48.1%) and 29.6% (95% CI 13.3-45.9%), respectively.

Proctectomy

In our previous analysis through Q2 2021, open surgery was the predominant approach at 45.4%, followed by laparoscopic at 30.4% and robotic at 24.2%. We had predicted robotic surgery would become the most common minimally invasive technique by 2025, reaching 32.3% (95% CI 23.1-41.4%). The data through 2023 (**Figure 3a**) showed that robotic surgery surpassed laparoscopy earlier than predicted at the beginning of 2022, reaching 31.6% by Q4 2023, while laparoscopic surgery declined to 22.5%. However, open surgery maintained a higher share than forecasted at 45.8%, as expected. Our updated Vector Autoregressive model, incorporating data through Q4 2023, predicts a steady decline in laparoscopic surgery to 20.1% by Q4 2026 (95%CI 3.7-36.4%), while robotic surgery is expected to further increase to 38.3% (95%CI 22.0-54.7%) and open surgery to decrease and stabilize at 41.6% (95%CI 17.7-65.5%), with respective 95% confidence intervals widening considerably over the forecast period (**Figure 3b**).

Pancreatectomy

In our previous analysis through Q2 2021, open surgery dominated 72.0% of cases, while laparoscopic and robotic approaches accounted for 13.2% and 14.8%, respectively. Our initial forecast predicted robotic surgery would reach 26.0% (95% CI 20.0-32.0%) by 2025, surpassing laparoscopy, which was expected to decline to 6.6%. The data through 2023 confirmed this transition (**Figure 4a**), though it occurred slightly later than predicted. By Q4 2023, robotic surgery had become the preferred minimally invasive approach at 19.9%, while laparoscopic surgery declined to 14.1% and open surgery remained predominant at 66%. Our updated Vector Autoregressive model projects that by Q4 2026 (**Figure 4b**), robotic surgery will continue its upward trajectory to reach 29.4% (95% CI 22.0-36.8%) of cases, with open surgery decreasing to

56.8% (95% CI 32.4-81.2%) and laparoscopic surgery further declining to 13.8% (95% CI 7.4-20.3%).

Hepatectomy

Our previous analysis through Q2 2021 showed open surgery as the dominant approach at 66.3%, with laparoscopic at 25.6% and robotic at 8.2%. We had predicted open surgery would remain the most widespread technique in 2025 at 70.0% (95% CI 26.2-100.0%), with laparoscopy at 19.3% and robotic at 10.8%. The data through 2023 (**Figure 5a**) revealed a more rapid adoption of robotic surgery than anticipated, reaching 15.3% by Q4 2023, while laparoscopic approach maintained 24.5% and open surgery decreased to 60.2%. Our updated Vector Autoregressive model now forecasts a continued acceleration in robotic surgery adoption, projecting it to reach 67.1% (95% CI 57.3-76.9%) by Q4 2026, with laparoscopic surgery declining to 16.5% (95% CI 4.3-28.7%) and open surgery decreasing further to 16.4% (95% CI 0.0-55.2%) (**Figure 5b**).

Esophagectomy

Our previous analysis through Q2 2021 showed open surgery at 36.2%, laparoscopic at 32.8%, and robotic at 30.9%. Despite noting significant uncertainty in our predictions due to smaller case numbers, we forecasted robotic surgery would become the predominant approach by early 2022, reaching 52.3% by 2025. The actual data through 2023 validated this prediction, though with a slightly delayed timeline (**Figure 6a**): robotic surgery became the most common approach in Q3 2023, reaching 36.9% of cases by Q4 2023, while laparoscopic surgery accounted for 33.5% and open surgery for 29.4%. Our updated Vector Autoregressive model (**Figure 6b**), incorporating this additional data, projects that by Q4 2026, robotic surgery will further consolidate its position at 63.3% (95% CI 34.7-91.9%), with laparoscopic surgery at 32.7% (95% CI 2.8-62.6%) and open surgery declining to 3.9% (95% CI 0.0-37.8%).

DISCUSSION

The data from 2021-2023 validate that the observed shift from laparoscopy to robotic surgery is not a temporary trend but a fundamental and enduring transformation in surgical history. Moreover, the persistent predominance of open surgery in several specialties suggests opportunities for broader adoption of minimally invasive approaches.

Our updated analysis reveals some interesting deviations from our original predictions. While some procedure volumes exceeded our previous 95% confidence intervals in absolute numbers, this likely reflects an overall increase in surgical case volumes rather than inaccurate modeling. When examining the relative proportions of surgical approaches, the actual percentages all remained within our predicted confidence intervals (**Table 1**). However, our new predictions through 2026 should be interpreted cautiously for several reasons. First, they incorporate six months of interpolated data from 2021, which may not perfectly reflect actual surgical volumes during that period. Second, they include two years of data (2022-2023) coded under a different classification system for surgical approaches, potentially introducing some inconsistency in trend analysis.

Finally, due to a limited number of temporal observations, the widening confidence intervals in our latest predictions highlight the increasing uncertainty in forecasting further into the future, especially amid rapid technological advancements in surgery.

This shift, however, raises several critical issues that the surgical community must address to ensure a smooth and effective transition within this rapidly evolving technological landscape.

First, surgical training must fundamentally change (17). With the increasing prevalence of robotic platforms, residency programs must adapt to provide comprehensive robotic surgical training. This includes developing technical proficiency in robotic manipulation, a thorough understanding of the nuances of various robotic platforms, instrument handling, and troubleshooting (18, 19). Established surgeons, primarily trained in laparoscopy, will require access to robust continuing medical education and training to acquire robotic proficiency. Simulation training, proctoring programs, and hands-on workshops will be essential to bridge the experience gap and build a competent robotic surgical workforce (20). Developing standardized curricula and assessment tools for robotic surgical skills will be crucial for maintaining training quality and consistency (21).

Second, surgical practice itself must evolve. Surgeons and hospitals must adapt workflows, operating room setups, and staffing models to accommodate robotic procedures effectively. This includes optimizing OR layouts for robotic equipment, training support staff in robotic assistance, developing standardized protocols for robotic cases (including emergent robotic surgery capability), and educating the entire surgical team—from scrub nurses to anesthesiologists—on the specifics of robotic procedures (22-25). Hospitals may need to invest in infrastructure upgrades, such as dedicated robotic ORs and specialized equipment, to meet the growing demand for robotic surgery. Postoperative care protocols may also require adjustments for patients undergoing robotic procedures (26). The emergence of new robotic platforms will necessitate ongoing evaluation and integration of these technologies, potentially requiring further workflow adjustments and training (27).

Third, laparoscopic surgeons must adapt to the evolving landscape of surgical technology and embrace robotic surgery. While laparoscopic skills remain valuable and should be maintained in surgical curricula, surgeons who resist robotic surgery adoption risk marginalization. Laparoscopic surgeons must recognize this shift and actively pursue robotic skills acquisition. Given their existing foundation in minimally invasive techniques, the transition to robotic surgery should, in many cases, be more efficient and streamlined (28-30). Embracing this technology ensures continued professional relevance and allows surgeons to offer patients the latest, potentially most beneficial surgical approaches. Moreover, experienced laparoscopic surgeons could bring valuable skills and insights that can refine and optimize robotic platforms and techniques.

A fourth key consideration is the integration of additional surgical platforms, a pivotal development poised to further drive robotic adoption. The emergence of new market competitors is expected to yield several far-reaching consequences (31). Notably, increased competition will likely accelerate technological innovation as platforms strive to offer enhanced surgical capabilities (32, 33). Furthermore, such market diversification is expected to substantially reduce the high costs associated with current robotic systems, thereby democratizing access across a variety of healthcare settings, including those with limited resources (34). The development of interoperability standards could also foster a more cohesive surgical ecosystem, empowering surgeons to select and utilize the unique advantages of different systems based on specific procedural needs (35). Consequently, expanded platform availability will likely hasten the adoption of minimally invasive approaches and the standardization of robotic techniques, potentially leading to measurable improvements in clinical outcomes.

Finally, the future of robotic surgery is promising. Technological advancements promise even more sophisticated robotic platforms with enhanced capabilities, including improved dexterity and greater capabilities. Integrating artificial intelligence and machine learning will likely play a crucial role, assisting surgeons with procedure planning, real-time decision-making, and even automating specific surgical tasks (35-38). Telesurgery could expand access to specialized surgical care in underserved areas (39, 40). Increasing competition among robotic platform developers will likely drive innovation, accelerate the development of these advanced features, and potentially decrease costs, further expanding adoption (41).

Several limitations of this study warrant consideration. First, the ACS-NSQIP database represents approximately 20% of surgical cases from participating institutions, potentially introducing selection bias. Second, the structural changes in data collection after 2022, particularly in surgical approach coding, required methodological adaptations that could affect trend analysis. Third, the interpolation of missing data for Q3-Q4 2021 assumes linear progression, which may not perfectly reflect actual surgical volumes during that period. To assess the robustness of our findings, we conducted a sensitivity analysis using alternative interpolation methods, namely spline and polynomial interpolation. Given that only two data points were missing, and the missing values were not located at the end of the series, the prediction results across all three interpolation methods were nearly identical, supporting the robustness of our modeling approach. Thus, we ultimately selected linear interpolation for its simplicity and effectiveness in this context. Fourth, the confidence intervals of our predictions widen considerably as they extend further into the future, reflecting increasing uncertainty. Finally, the database does not capture essential variables such as surgeon experience, hospital volume, or specific robotic platforms, which could influence surgical approach selection. High-volume centers and experienced surgeons may adopt robotic technology more rapidly, potentially accelerating the observed trends in certain institutions while creating geographic disparities in adoption rates. Additionally, differences between robotic platforms in terms of cost, capabilities, and availability may influence institutional choices, though our aggregate analysis captures the overall directional shift toward robotic surgery regardless of specific platform variations.

CONCLUSION

The transition toward robotic surgery continues across surgical specialties, though at varying rates and extents. Robotics has achieved dominance in urologic procedures and shows accelerating adoption in complex operations such as hepatectomy and esophagectomy. While traditional laparoscopy is significant in some procedures, particularly colectomy, its utilization consistently declines across most specialties. The persistently high rates of open surgery, especially in pancreatic and rectal operations, suggest opportunities remain for expanding minimally invasive approaches. These findings have important implications for surgical training, healthcare infrastructure, and resource allocation as the field continues its technological evolution.

REFERENCES

1. Haywood N, Scott J, Zhang A, Hallowell P, et al. Characterization of the robotic surgery experience in minimally invasive surgery fellowships from 2010 to 2021. Surg Endosc. 2023;37(12):9393-8.
2. Stewart CL, Ituarte PHG, Melstrom KA, et al. Robotic surgery trends in general surgical oncology from the National Inpatient Sample. Surg Endosc. 2019;33(8):2591-601.
3. Sheetz KH, Claflin J, Dimick JB. Trends in the Adoption of Robotic Surgery for Common Surgical Procedures. JAMA Netw Open. 2020;3(1):e1918911.
4. Manisundaram N, Childers CP, Hu CY, et al. Rise in Minimally Invasive Surgery for Colorectal Cancer Is Associated With Adoption of Robotic Surgery. Dis Colon Rectum. 2025.
5. Violante T, Ferrari D, Novelli M, et al. P1104 Shifting Surgical Landscape in Crohn's Colitis: Laparoscopic Supremacy and Robotic Upsurge. Journal of Crohn's and Colitis. 2024;18(Supplement_1):i1985-i.
6. Ferrari D, Violante T, Novelli M, et al. P1126 Navigating the Future: Minimally Invasive Surgery Trends in Ulcerative Colitis. Journal of Crohn's and Colitis. 2024;18(Supplement_1):i2019-i.
7. Muaddi H, Hafid ME, Choi WJ, et al. Clinical Outcomes of Robotic Surgery Compared to Conventional Surgical Approaches (Laparoscopic or Open): A Systematic Overview of Reviews. Ann Surg. 2021;273(3):467-73.
8. Violante T, Ferrari D, Novelli M, Behm KT, et al. Evaluating the Impact of Robotic IPAA: A Case-Matched Analysis from a High-Volume Center. Ann Surg. 2024.
9. Leal Ghezzi T, Campos Corleta O. 30 Years of Robotic Surgery. World J Surg. 2016;40(10):2550-7.
10. Robot-Assisted Surgery for Noncancerous Gynecologic Conditions: ACOG COMMITTEE OPINION, Number 810. Obstet Gynecol. 2020;136(3):e22-e30.
11. Cheng CL, Rezac C. The role of robotics in colorectal surgery. Bmj. 2018;360:j5304.
12. Erozkan K, Gorgun E. Robotic colorectal surgery and future directions. Am J Surg. 2024;230:91-8.
13. Ferrari D, Violante T, Novelli M, et al. The death of laparoscopy. Surg Endosc. 2024;38(5):2677-88.
14. von Elm E, Altman DG, Egger M, et al. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. Lancet. 2007;370(9596):1453-7.
15. Hamilton JD. Time series analysis: Princeton university press; 1994.
16. Johansen S. Likelihood-Based Inference in Cointegrated Vector Autoregressive Models: Oxford University Press; 1995 01 Nov 2003.
17. Jogerst KM, Coe TM, Petrusa E, et al. Multidisciplinary perceptions on robotic surgical training: the robot is a stimulus for surgical education change. Surg Endosc. 2023;37(4):2688-97.
18. Chen R, Rodrigues Armijo P, Krause C, et al. A comprehensive review of robotic surgery curriculum and training for residents, fellows, and postgraduate surgical education. Surg Endosc. 2020;34(1):361-7.
19. Seeliger B, Pavone M, Schröder W, et al. Skill progress during a dedicated societal robotic surgery training curriculum including several robotic surgery platforms. Surg Endosc. 2024;38(9):5405-12.

20. Fong Y, Buell JF, Collins J, et al. Applying the Delphi process for development of a hepatopancreaticobiliary robotic surgery training curriculum. Surg Endosc. 2020;34(10):4233-44.
21. Hertz P, Houlind K, Jepsen J, et al. Identifying curriculum content for a cross-specialty robotic-assisted surgery training program: a Delphi study. Surg Endosc. 2022;36(7):4786-94.
22. Gage D, Neilson T, Pino MG, Eiferman D, et al. Establishment of a 24/7 robotic acute care surgery program at a large academic medical center. Surg Endosc. 2024;38(8):4663-9.
23. Catchpole K, Cohen T, Alfred M, et al. Human Factors Integration in Robotic Surgery. Hum Factors. 2024;66(3):683-700.
24. Møller L, Olsen RG, Jørgensen L, et al. Training and education of operating room nurses in robot-assisted surgery: a systematic review. Surg Endosc. 2024;38(12):7024-36.
25. Lunardi N, Abou-Zamzam A, Florecki KL, et al. Robotic Technology in Emergency General Surgery Cases in the Era of Minimally Invasive Surgery. JAMA Surg. 2024;159(5):493-9.
26. Stringfield SB, Parry LA, Eisenstein SG, et al. Experience with 10 years of a robotic surgery program at an Academic Medical Center. Surg Endosc. 2022;36(3):1950-60.
27. Lendvay TS, Hannaford B, Satava RM. Future of robotic surgery. Cancer J. 2013;19(2):109-19.
28. Pietersen PI, Hertz P, Olsen RG, et al. Transfer of skills between laparoscopic and robot-assisted surgery: a systematic review. Surg Endosc. 2023;37(12):9030-42.
29. Schmidt MW, Fan C, Köppinger KF, et al. Laparoscopic but not open surgical skills can be transferred to robot-assisted surgery: A systematic review and meta-analysis. World J Surg. 2024;48(1):14-28.
30. Quinn KM, Runge LT, Griffiths C, et al. Laparoscopic vs robotic inguinal hernia repair: a comparison of learning curves and skill transference in general surgery residents. Surg Endosc. 2024;38(6):3346-52.
31. Peters BS, Armijo PR, Krause C, et al. Review of emerging surgical robotic technology. Surg Endosc. 2018;32(4):1636-55.
32. Farinha R, Puliatti S, Mazzone E, et al. Potential Contenders for the Leadership in Robotic Surgery. J Endourol. 2022;36(3):317-26.
33. Kinross JM, Mason SE, Mylonas G, et al. Next-generation robotics in gastrointestinal surgery. Nat Rev Gastroenterol Hepatol. 2020;17(7):430-40.
34. Landi S, Maistri G, Orsini LP, et al. Supporting managerial decisions: a comparison of new robotic platforms through time-driven activity-based costing within a value-based healthcare framework. BMC Health Serv Res. 2025;25(1):470.
35. de'Angelis N, Khan J, Marchegiani F, et al. Robotic surgery in emergency setting: 2021 WSES position paper. World J Emerg Surg. 2022;17(1):4.

36. Vasey B, Lippert KAN, Khan DZ, et al. Intraoperative Applications of Artificial Intelligence in Robotic Surgery: A Scoping Review of Current Development Stages and Levels of Autonomy. Ann Surg. 2023;278(6):896-903.
37. Yip M, Salcudean S, Goldberg K, et al. Artificial intelligence meets medical robotics. Science. 2023;381(6654):141-6.
38. Zhang C, Hallbeck MS, Salehinejad H, et al. The integration of artificial intelligence in robotic surgery: A narrative review. Surgery. 2024;176(3):552-7.
39. Li J, Yang X, Chu G, Feng W, et al. Application of Improved Robot-assisted Laparoscopic Telesurgery with 5G Technology in Urology. Eur Urol. 2023;83(1):41-4.

40. Zhou F, Guo B, Lv H, et al. Application of 5G Remote Robotic-assisted Laparoscopy in Urological Surgery: A Small Sample Analysis. Urology. 2024.
41. Sarin A, Samreen S, Moffett JM, et al. Upcoming multi-visceral robotic surgery systems: a SAGES review. Surg Endosc. 2024;38(12):6987-7010.

Figure1. Trends of open, laparoscopic, and robotic approach for prostatectomy (a), nephrectomy (b), and cystectomy (c).

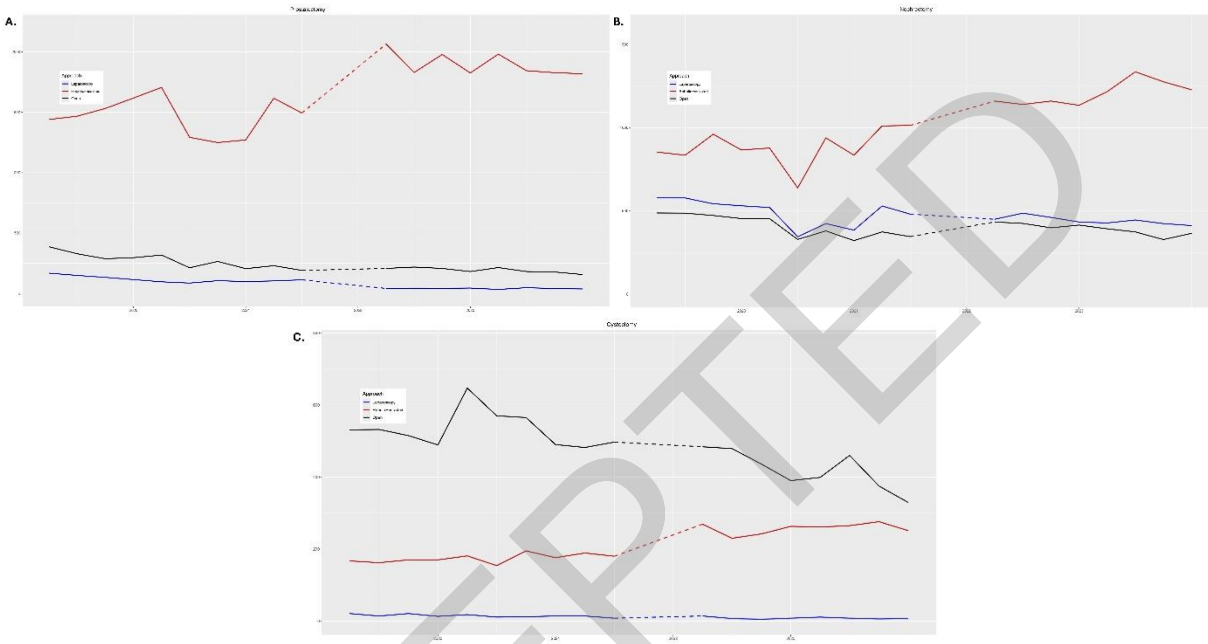

Figure 2. Trends of open, laparoscopic, and robotic approach for colectomy (a), updated Vector Autoregressive model for colectomy (b).

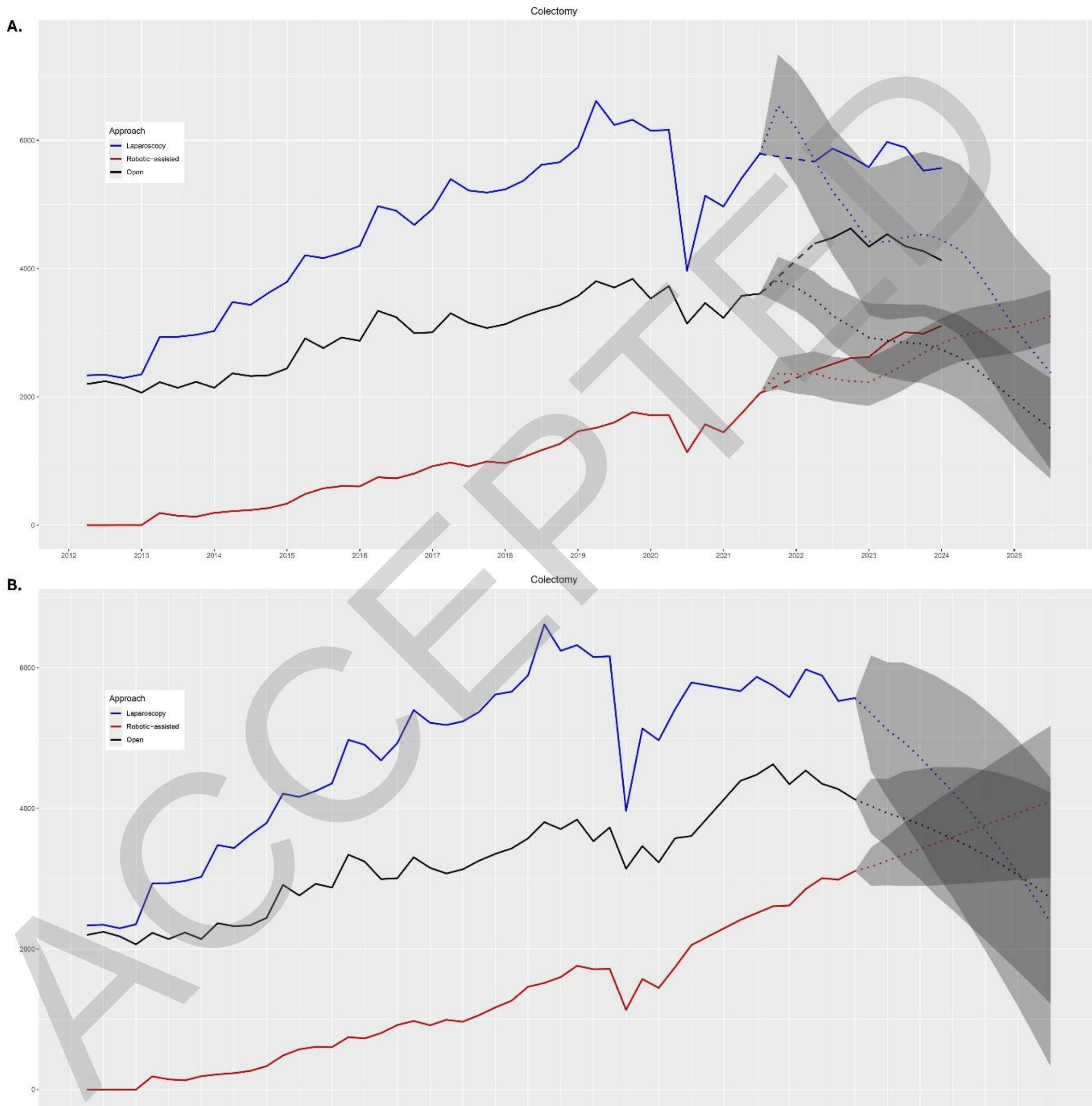

Figure 3. Trends of open, laparoscopic, and robotic approach for proctectomy (a), updated Vector Autoregressive model for proctectomy (b).

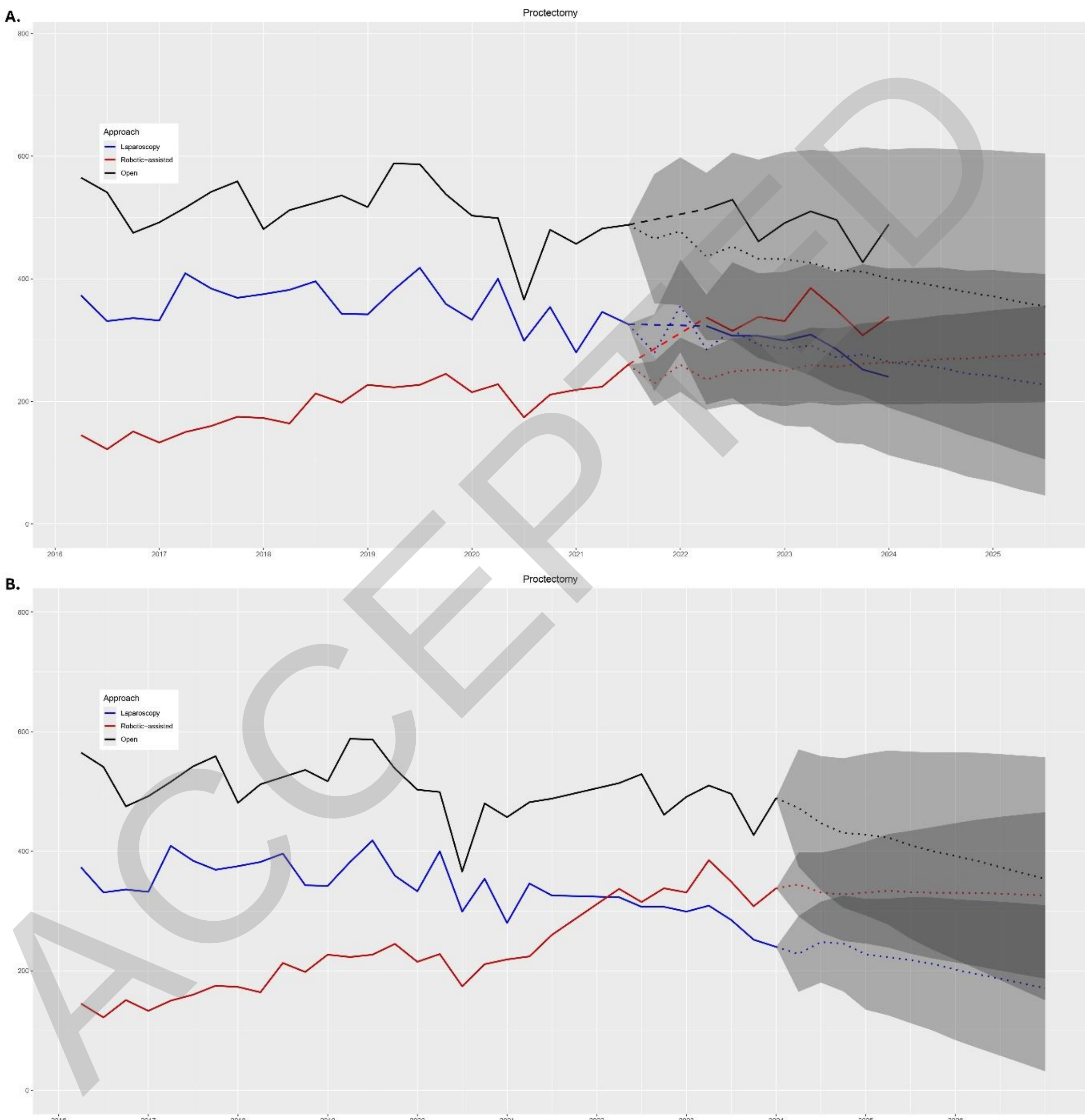

Figure 4. Trends of open, laparoscopic, and robotic approach for pancreatectomy (a), updated Vector Autoregressive model for pancreatectomy (b).

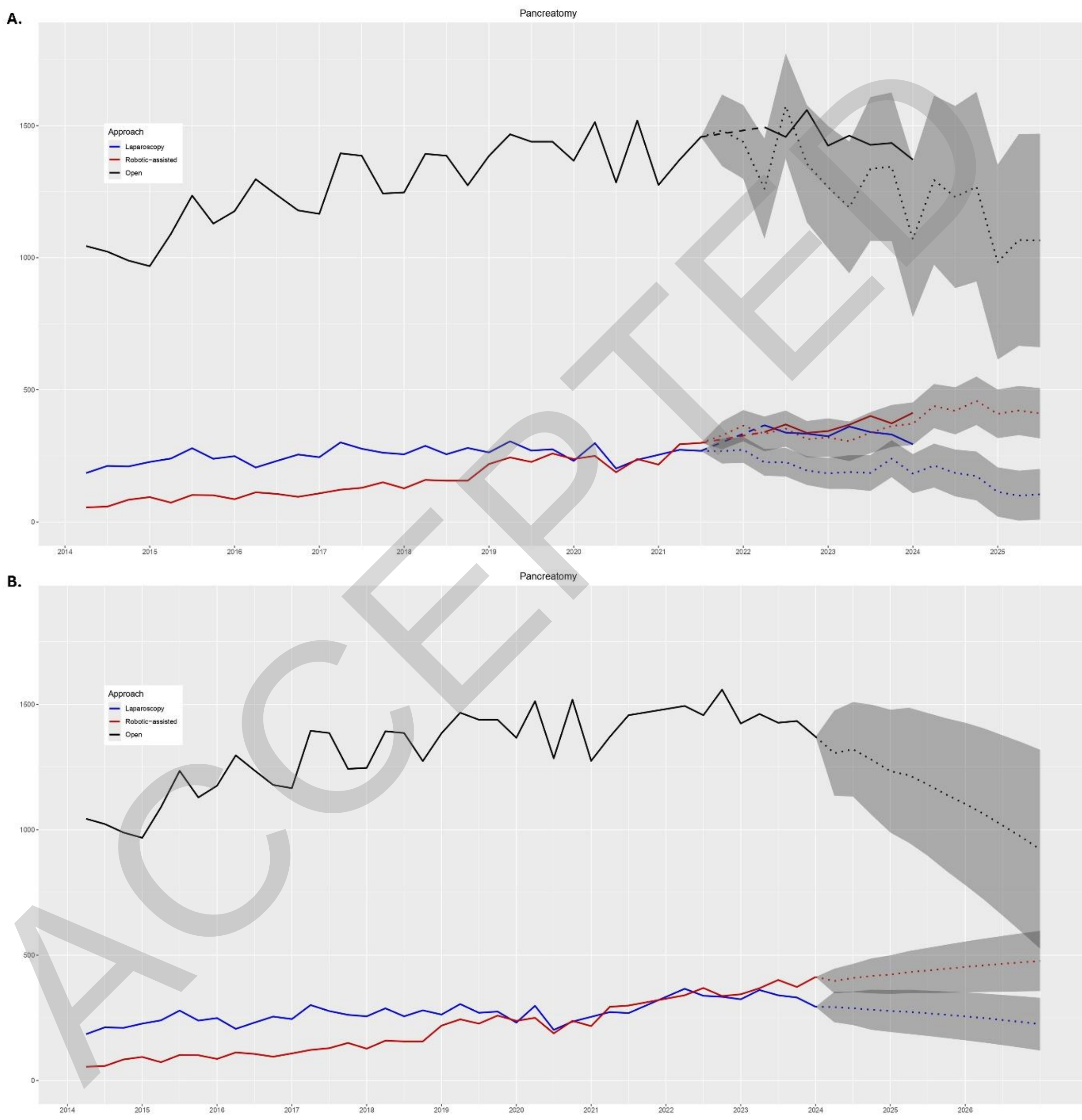

Figure 5. Trends of open, laparoscopic, and robotic approach for hepatectomy (a), updated Vector Autoregressive model for hepatectomy (b).

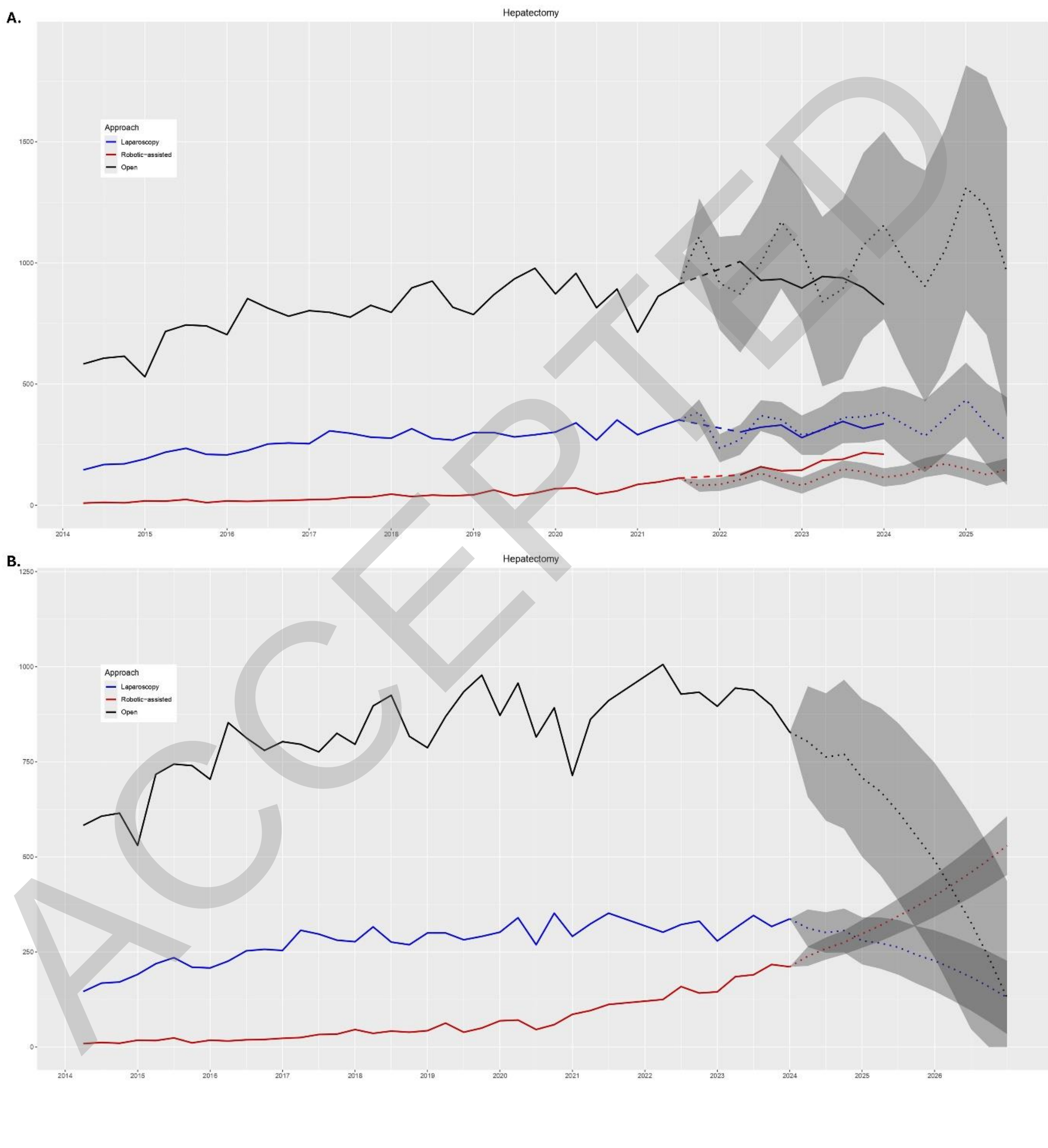

Figure 6. Trends of open, laparoscopic, and robotic approach for esophagectomy (a), updated Vector Autoregressive model for esophagectomy (b).

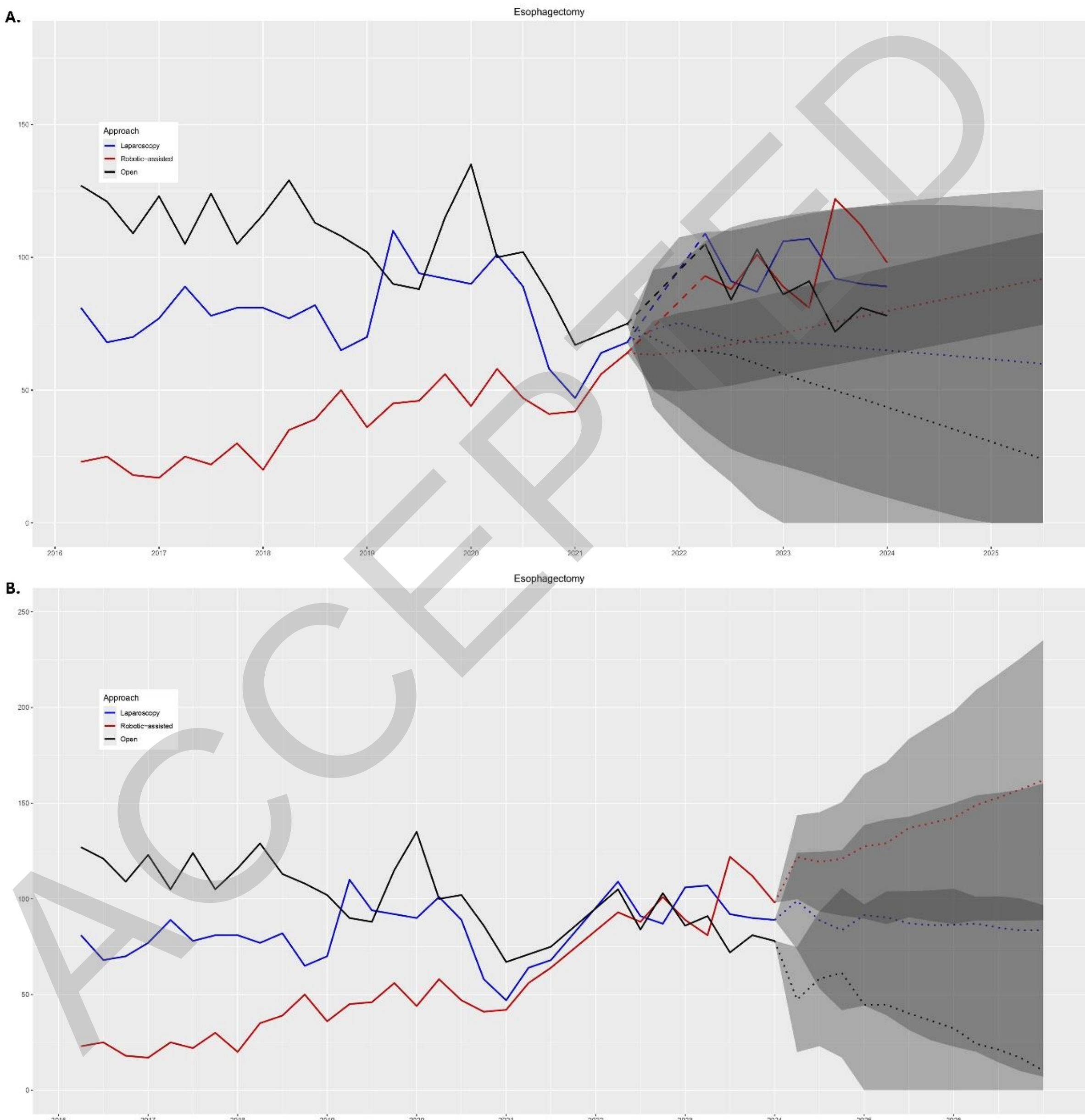

Table 1. Comparison of surgical approach adoption from initial observations to future predictions. *First Observation* and *VAR Q4 2023 (Prediction)* data derived from previous publication[13]. Confidence intervals (95% CI) shown in parentheses.

Procedure	**Surgical approach**	**First observation** (Study start)	**VAR Q4 2023 (CI)** (Prediction)	**Actual Q4 2023** (Observed)	**VAR Q4 2026 (CI)** (Prediction)
Colectomy (2012)	**Robotic**	0%	26.7% (22.9%-30.6%)	24.2%	44.5% (32.8-56.3%)
	Laparoscopic	51.5%	45.2% (32.4%-57.9%)	43.5%	25.8% (3.5-48.1%)
	Open	48.5%	28.1% (22.0%-34.2%)	32.2%	29.6% (13.3-45.9%)
Hepatectomy (2014)	**Robotic**	1.2%	7.0% (4.7%-9.2%)	15.3%	67.1% (57.3-76.9%)
	Laparoscopic	19.8%	23.1% (16.5%-29.7%)	24.5%	16.5% (4.3-28.7%)
	Open	79%	69.9% (46.5%-93.4%)	60.2%	16.4% (0.0-55.2%)
Pancreatectomy (2014)	**Robotic**	4.3%	23.5% (15.9%-31.1%)	19.9%	29.4% (22.0-36.8%)
	Laparoscopic	14.4%	9.0% (6.9%-11.2%)	14.1%	13.8% (7.4-20.3%)
	Open	81.3%	67.5% (48.9%-86.1%)	66%	56.8% (32.4-81.2%)
Proctectomy (2016)	**Robotic**	13.4%	27.6% (20.7%-34.4%)	31.7%	38.3% (22.0-54.7%)
	Laparoscopic	34.4%	29.1% (13.6%-44.6%)	22.5%	20.1% (3.7-36.4%)
	Open	52.2%	43.3% (22.0%-64.7%)	45.8%	41.6% (17.7-65.5%)
Esophagectomy (2016)	**Robotic**	10%	40.8% (32.3%-49.4%)	31.7%	63.3% (34.7-91.9%)
	Laparoscopic	35.1%	34.6% (9.7%-59.5%)	22.5%	32.7% (2.8-62.6%)
	Open	54.9%	24.6% (0.0%-62.6%)	45.8%	3.9% (0.0-37.8%)