Short-Term Outcomes and Pathological Features of Laparoscopic Versus Open Radical Total Gastrectomy for pT4a Gastric Cancer

Ann. Ital. Chir., 2026 97, 9: 1624–1643
https://doi.org/10.62713/aic.4867

Bo Ding[1], Ke Liu[1], Ruyi Li[1], Zijian Liu[1], Shensi Chen[1]

[1]Department of Gastrointestinal Surgery, General Hospital of Ningxia Medical University, 750004 Yinchuan, Ningxia Hui Autonomous Region, China

AIM: The oncologic safety of laparoscopic radical total gastrectomy for pT4a gastric cancer remains debated, and the potential modifying role of Lauren histotype is unclear. This study aimed to develop an individualized prediction model for prolonged postoperative hospital stay to support risk-stratified rehabilitation. Secondary analyses compared perioperative outcomes between laparoscopic and open surgery, while exploratory subgroup analyses assessed potential effects of Lauren subtype.

METHODS: This single-center retrospective cohort study included consecutive patients with pT4a gastric adenocarcinoma undergoing radical total gastrectomy at General Hospital of Ningxia Medical University from January 2021 to December 2025. Among 302 patients, 153 underwent laparoscopic surgery and 149 underwent open surgery. One-to-one propensity score matching (PSM) generated a balanced cohort of 248 patients. Univariable and multivariable logistic regression identified independent predictors of prolonged postoperative hospital stay. Model performance was evaluated using receiver operating characteristic (ROC) curves, calibration analysis, decision curve analysis (DCA), and SHapley Additive exPlanations (SHAP). A nomogram was constructed for individualized risk estimation. Perioperative and oncological outcomes were compared, and interaction analyses were performed to explore potential effect modification by Lauren subtype.

RESULTS: After PSM, baseline characteristics were well balanced (all standardized mean differences <0.1). Multivariable analysis identified laparoscopic surgery (odds ratio [OR] = 0.47, 95% confidence interval [CI] 0.27–0.82, $p = 0.008$), specific N-stage categories and histological differentiation categories were associated with a lower risk of prolonged hospitalization, whereas increased intraoperative blood loss was associated with prolonged hospitalization. The prediction model achieved an area under the curve (AUC) of 0.73 (95% CI 0.67–0.79), with good calibration and clinical utility across threshold probabilities of 0.1–0.7. SHAP analysis indicated Node (N) stage and surgical approach as the two most influential predictors. Compared with open surgery, laparoscopic gastrectomy resulted in shorter incision length, reduced blood loss, earlier drain removal, and shorter postoperative and overall hospital stays (all $p < 0.05$), despite longer operative time. No significant differences were observed in lymph node retrieval, positive lymph node counts, or N stage distribution. Exploratory analyses demonstrated consistent favorable trends of laparoscopic surgery across Lauren subtypes, but no significant interaction was detected between surgical approach and Lauren classification (all $p_{\text{interaction}} > 0.05$).

CONCLUSIONS: Laparoscopic surgery, histological differentiation, N stage, and intraoperative blood loss independently predict prolonged postoperative hospitalization after radical total gastrectomy for pT4a gastric cancer. The proposed model may provide preliminary risk stratification for patients undergoing radical total gastrectomy for pT4a gastric cancer, although further validation is required. Laparoscopic D2 radical total gastrectomy offers comparable lymph node retrieval and pathological outcomes with improved short-term recovery outcomes. The potential influence of Lauren subtype requires validation in larger multicenter cohorts.

Keywords: pT4a gastric cancer; laparoscopic gastrectomy; Lauren classification; propensity score matching; perioperative outcomes

Introduction

Gastric cancer is one of the most prevalent malignancies worldwide, with approximately 1.1 million new cases and more than 760,000 deaths reported globally in 2020, representing a substantial disease burden [1]. In China, both the incidence and mortality of gastric cancer rank among the highest of all malignancies. Due to the low rate of early detection, more than half of cases are initially diagnosed with locally advanced or metastatic disease [2,3]. By virtue of its significant impact on patient outcomes, D2 lymphadenectomy–based radical total gastrectomy remains the standard treatment for pT4a gastric cancer [4]. However, patients with pT4a disease often experience extensive surgical trauma and pronounced postoperative inflammatory responses, which account for the considerable interindividual variability observed during the recovery phase. Postoperative hospital stay, as a comprehensive indicator of perioperative quality control, is closely asso-

Submitted: 23 June 2026 Revised: 7 August 2026 Accepted: 11 August 2026 Published: 15 September 2026
Correspondence to: Shensi Chen, Department of Gastrointestinal Surgery, General Hospital of Ningxia Medical University, 750004 Yinchuan, Ningxia Hui Autonomous Region, China (e-mail: jiaodasisi@163.com).
Editor: Xiaohua Jiang

ciated with in-hospital complications, healthcare resource utilization, and economic burden. Therefore, accurate identification of risk factors for delayed postoperative recovery and development of a disease-specific risk-stratification model represent a key clinical priority to refine perioperative precision management for patients with pT4a gastric cancer, constituting the primary objective of the present study.

With the advancement of minimally invasive surgery, laparoscopic radical total gastrectomy has been widely adopted for treating early gastric cancer. Multiple meta-analyses have demonstrated that laparoscopic surgery provides advantages, including reduced blood loss and faster recovery, with comparable oncological outcomes to open surgery [5,6]. The surgical approach acts as a modifiable determinant of postoperative recovery and serves as an essential covariate for models predicting postoperative length of stay. The CLASS-01 and KLASS-02 multicenter randomized controlled trials demonstrated that laparoscopic and open gastrectomy had comparable short-term complication rates and long-term survival outcomes in locally advanced gastric cancer, providing evidence supporting the broader application of laparoscopic techniques [7,8]. Nevertheless, subgroup data specifically focusing on pT4a patients remain limited, leaving uncertainty regarding the oncological equivalence of laparoscopy in this high-risk population. Under certain circumstances, surgeons remain cautious about its technical feasibility and the completeness of lymph node dissection, particularly in cases with extensive tumor invasion and severe adhesions [9]. Since the adequacy of lymphadenectomy is a key determinant of oncological radicality, insufficient D2 dissection may increase gastric cancer–specific mortality at 5 years in patients with pT4a disease [10]. Therefore, evaluation of alternative surgical approaches must prioritize maintaining oncological completeness.

Lauren classification is a widely recognized histological classification system for gastric cancer, consisting of intestinal, diffuse, and mixed subtypes. It reflects tumor growth patterns and biological behaviors, with substantial differences among subtypes in invasiveness, metastatic patterns, and prognosis [11,12]. From pathological and biological perspectives, variations in local invasion patterns among Lauren subtypes may influence the technical difficulty of laparoscopic dissection and the magnitude of postoperative inflammatory responses, potentially affecting postoperative hospitalization duration according to the surgical approach performed. However, previous comparative studies of surgical approaches have rarely considered the stratifying effect of Lauren classification. Whether patients with different pathological subtypes derive differential recovery benefits from laparoscopic surgery remains unclear, with current evidence limited by small sample sizes and inconsistent findings [13]. Lauren classification was examined solely as an exploratory effect modifier in subgroup interaction analyses. These analyses were not predefined primary endpoints; their outputs are hypothesis-generating rather than confirmatory.

Currently, systematic analyses and dedicated prediction models for prolonged postoperative hospitalization after pT4a gastric cancer surgery remain lacking. Existing models are mainly developed based on findings of heterogeneous gastric cancer populations across all stages and do not adequately account for the unique characteristics of pT4a disease, including aggressive tumor invasion and extensive surgical trauma, thereby limiting their clinical applicability for high-risk patients [14]. Accordingly, constructing an individualized risk-prediction model for delayed recovery after radical total gastrectomy and identifying key determinants of hospital recovery carry substantial clinical relevance. Against this background, the present study had three hierarchical objectives. The primary objective was to identify independent predictors of prolonged postoperative hospital stay in pT4a gastric cancer, develop and validate an individualized risk prediction model, and establish a quantitative tool for postoperative risk stratification. The secondary objective was to compare perioperative recovery and pathological outcomes between laparoscopic and open D2 gastrectomy, and characterize the impact of surgical approach as a modifiable factor on postoperative recovery. Lastly, the exploratory objective was to perform interaction analyses stratified by Lauren histotype, exploring whether histological subtype modifies the association between surgical approach and postoperative outcomes, so as to generate hypotheses to inform future precision-based surgical selection.

Methods

Study Design

This single-center retrospective cohort study was conducted using electronic medical records and pathological databases from General Hospital of Ningxia Medical University. A three-tier analytical framework was predefined: primary, secondary, and exploratory analyses. The primary objective was to identify independent risk factors for prolonged postoperative hospital stay following radical total gastrectomy with D2 lymphadenectomy for pT4a gastric adenocarcinoma and to develop an individualized risk-prediction model. The secondary objective was to estimate the effects of surgical approach on perioperative safety, postoperative recovery, and oncological radicality, providing contextual interpretability for the surgical-approach variable in the primary prediction model. The exploratory objective was to test the potential effect-modifying role of Lauren classification on surgical outcomes exclusively to generate hypotheses for future investigations. This exploratory analysis was not designed to establish the definitive predictive value of Lauren classification, nor to support its use as a basis for surgical decision-making in clinical practice. Surgical approach was incorporated as a modifiable perioperative co-

variate into the primary prediction model, whereas Lauren classification was assessed for potential effect modification in predefined exploratory subgroup and interaction analyses with strictly hypothesis-generating interpretive boundaries. Propensity score matching (PSM) was applied to mitigate selection bias arising from non-random surgical-group assignment in this retrospective design. PSM served as the shared methodological foundation for all three tiers of analyses, and the PSM-matched cohort was used for comparative analyses and prediction model development; therefore, the developed model should be interpreted within the characteristics of this balanced retrospective cohort.

This investigation strictly adhered to the ethical principles outlined in the Declaration of Helsinki. The study protocol received formal authorization from the Institutional Review Board of the General Hospital of Ningxia Medical University (Ethics Approval Number: KYLL-2026-1127). The requirement to obtain written informed consent was waived due to the retrospective nature of the chart review, absence of additional patient interventions, and full anonymization of all clinical and pathological identifiers to protect participant confidentiality.

Study Population

We consecutively enrolled patients with primary gastric adenocarcinoma who underwent radical total gastrectomy at the Department of Gastrointestinal Surgery, General Hospital of Ningxia Medical University, between January 2021 and December 2025.

Inclusion Criteria

The inclusion criteria of this study are as follows:

1. Age >18 years, with no sex restrictions.
2. Primary gastric adenocarcinoma confirmed by preoperative gastroscopic biopsy and pathological examination.
3. Postoperative pathological staging consistent with pT4a disease according to the 8th edition of the American Joint Committee on Cancer (AJCC) Tumor–Node–Metastasis (TNM) staging system, with no evidence of distant metastasis (M0) on preoperative cross-sectional imaging and final pathological examination.
4. Underwent either laparoscopic radical total gastrectomy or open radical total gastrectomy with complete standard D2 lymphadenectomy.
5. No history of neoadjuvant therapy, including chemotherapy, radiotherapy, targeted therapy, or immunotherapy, before surgery.
6. No history of synchronous or metachronous malignancies at other anatomical sites.

Exclusion Criteria

The exclusion criteria of this study are as follows:

1. Emergency surgery for tumor-related hemorrhage, perforation, or obstruction, or receipt of palliative non-curative resection.
2. Presence of concurrent primary malignant tumor at another anatomical site.
3. Severe pre-existing dysfunctions of critical organs (cardiac, pulmonary, hepatic, renal) that preclude radical total gastrectomy.
4. Psychiatric disorders that impair treatment adherence and postoperative follow-up.
5. Pregnancy or lactation.
6. Incomplete key clinical or pathological documentation, premature self-discharge, or loss to follow-up during inpatient care.

Group Allocation and Stratification Variable

Patients were stratified into the laparoscopic surgery (LG) group and open surgery (OG) group, according to the surgical type. Surgical approach was not treated as a standalone primary endpoint. Instead, it was entered into the primary prediction model as a modifiable covariate influencing postoperative recovery to quantify its independent effect on prolonged postoperative hospital stay.

Postoperative pathological Lauren classification served as the stratification factor for exploratory subgroup analyses only. In analyses, the patients were categorized according to the Lauren classification into three distinct subgroups: intestinal type, diffuse type, and mixed type. Notably, Lauren classification was applied solely as an exploratory variable for hypothesis generation; it was not validated as a clinical predictor for surgical approach selection, and no recommendations for patient-tailored surgical decision-making based on Lauren subtypes were derived from this study. All histological slides were independently reviewed in a blinded fashion by two pathologists who had over 10 years of specialized experience in diagnosing gastrointestinal malignancies. Discrepant diagnoses were resolved via multidisciplinary pathological consensus review to reach a unified final classification.

Data Extraction and Variable Definitions

All clinical data were extracted from the integrated institutional electronic platforms, including the electronic medical record (EMR) system, anesthesia information system, pathological information system (PIS), and laboratory information system (LIS). Two trained investigators independently extracted and cross-validated all data. Conflicting entries were resolved by reviewing the original hard-copy medical records to ensure data integrity and accuracy.

Demographic and Baseline Characteristics

The following variables were collected as covariates for PSM and confounder adjustment in regression models, and none were defined as independent study endpoints:

1. Demographic characteristics: age, sex, body weight, height, with body mass index (BMI, kg/m^2) calculated.

2. Preoperative laboratory parameters (collected within one week before surgery, prior to any invasive intervention or antineoplastic therapy):
(1) Tumor biomarkers: serum carcinoembryonic antigen (CEA) and carbohydrate antigen 19-9 (CA19-9);
(2) Nutritional and inflammatory indices: hemoglobin (Hb), serum albumin, neutrophil count, lymphocyte count, platelet count, and monocyte count;
(3) Systemic inflammatory indices: The neutrophil-to-lymphocyte ratio (NLR), platelet-to-lymphocyte percentage ratio (PL%R), and lymphocyte-to-monocyte ratio (LMR) were derived from the pre-treatment complete blood count (CBC) with differential. The original dataset retained leukocyte differential percentages (relative values) but not absolute leukocyte counts. NLR and LMR were therefore calculated as the ratios of the corresponding differential percentages (neutrophil % / lymphocyte % and lymphocyte % / monocyte %, respectively). Because the absolute neutrophil, lymphocyte, and monocyte counts are each the product of the total white blood cell count and the respective differential percentage, the total white blood cell count cancels in these ratios; consequently, NLR and LMR computed from differential percentages are mathematically equivalent to those computed from absolute counts. PL%R was calculated as the absolute platelet count divided by the lymphocyte percentage, in accordance with Al Gazzar et al. [15], who defined the platelet-to-lymphocyte percentage ratio as a distinct inflammatory index separate from the conventional platelet-to-lymphocyte ratio. As absolute lymphocyte counts were unavailable in our dataset, the conventional PLR could not be computed; PL%R is therefore reported throughout the manuscript;
(4) Tumor pathological features: tumor location, maximum tumor diameter, gross morphological type (ulcerative, protrusive, etc.), histological differentiation, and Lauren classification.

Surgical and Postoperative Recovery Parameters

The recovery parameters used in this study are listed as follows:
(1) Operative time: defined as the duration from skin incision to completion of skin closure (h).
(2) Incision length: measured using a standardized protocol across both groups. The linear skin incision length was recorded: for the laparoscopic group, the length of the upper abdominal auxiliary incision was measured (excluding trocar wounds); for the open group, the length of the midline upper-abdominal main incision was measured. Circulating nurses performed immediate measurements with sterile rulers upon skin closure. Consistent personnel, measuring tools, and timing guaranteed inter-group comparability.
(3) Intraoperative blood loss: estimated using the combined method of suction volume after subtracting irrigation fluid volume and gauze weight measurement (mL).
(4) Time to abdominal drainage tube removal: defined as the interval from the day of surgery to the day on which the final abdominal drain was formally removed, based on documented clinical orders. Delayed removal due to postoperative complications was recorded according to the actual date of drain withdrawal. This uniform definition minimized variability caused by individual institutional practices for early drain removal.
(5) Postoperative hospital stay: defined as the number of days from completion of surgery to the day of discharge after meeting discharge criteria. A standardized discharge protocol was applied to reduce heterogeneity; however, postoperative hospital stay may still be influenced by institutional clinical management practices and does not solely reflect physiological recovery.
(6) Total hospital stay: defined as the number of days from admission to discharge.
(7) Postoperative complications: All surgery-related complications occurring within 30 days after surgery were recorded and graded according to the Clavien–Dindo classification. The overall complication rate and incidence of major complications (grade ≥III) were calculated.
Discharge was considered when all standardized criteria were met, including ability to consume an oral semi-liquid diet without assistance, maintenance of normal body temperature, satisfactory wound healing without redness or discharge, removal of abdominal drainage tubes, and no ongoing requirement for intravenous fluid or supportive therapy.

Tumor Pathological Characteristics

Parameters related to tumor pathological characteristics were collected, including tumor anatomical location, maximum tumor diameter, gross morphological subtype (ulcerative, protuberant, etc.), histological differentiation grade, Lauren classification, total number of harvested lymph nodes, number of metastatic lymph nodes, and pathological N stage (according to the 8th AJCC TNM staging framework).

Surgical Procedures

All procedures were performed by the same gastrointestinal surgical team, with operations conducted by senior surgeons with more than 10 years of experience in gastric cancer radical surgery. The primary laparoscopic surgeon had completed more than 500 laparoscopic radical gastrectomies and had surpassed the learning curve, ensuring technical consistency and procedural homogeneity between groups. All surgeries were conducted in strict adherence to the D2 lymphadenectomy standards recommended by the Japanese Gastric Cancer Treatment Guidelines (5th edition). Postoperatively, all patients were managed according to a standardized enhanced recovery after surgery (ERAS) protocol.
For the laparoscopic surgery group, a conventional five-port approach was used to establish access, followed

by CO_2 pneumoperitoneum with intra-abdominal pressure maintained at 12–14 mmHg. Intracorporeal procedures included complete laparoscopic dissection of perigastric ligaments, skeletonization and division of the left gastric, right gastric, and bilateral gastroepiploic vessels, standard D2 lymph node dissection, and distal esophageal mobilization. A 4–6 cm upper abdominal auxiliary incision was created for extracorporeal specimen extraction and digestive tract reconstruction using esophagojejunostomy with Roux-en-Y reconstruction; laparoscopic intracorporeal reconstruction was not performed.

For the open surgery group, an upper midline abdominal incision extending around the umbilicus was used for abdominal access. Total gastrectomy, D2 lymphadenectomy, and esophagojejunostomy with Roux-en-Y reconstruction were performed according to standard open surgical procedures.

In both groups, one to two abdominal drainage tubes were routinely placed at the Winslow foramen and left subdiaphragmatic space.

All patients were managed using the same standardized ERAS protocol, which included preoperative fasting for 6 hours with clear fluids withheld for 2 hours before surgery; goal-directed intraoperative fluid management to maintain fluid balance; multimodal postoperative analgesia (patient-controlled intravenous analgesia combined with nonsteroidal anti-inflammatory drugs); passive bed activity beginning on postoperative day 1, followed by encouraged ambulation from postoperative day 2; and initiation of oral water intake on postoperative day 1, followed by gradual transition from liquid to semi-liquid diets.

Abdominal drainage tubes were removed according to the standardized criteria, which included stable abdominal signs, absence of fever or abdominal pain, clear drainage fluid, drainage volume <200 mL over 24 hours, and clinical exclusion of complications such as anastomotic leakage or intra-abdominal bleeding. Drainage management, complication assessment, and discharge decision-making were executed in compliance with the same clinical protocols to minimize the influence of management heterogeneity on patient outcomes.

Outcome Measures

Outcome measures and analytical workflows were structured according to the three-tier framework (primary-secondary-exploratory). All analyses were performed on the PSM-balanced cohort.

Primary Analysis: Identification of Risk Factors and Construction of Prediction Model for Prolonged Postoperative Hospital Stay (Primary Endpoint)

Prolonged postoperative hospital stay was designated as the primary endpoint. This analysis aimed to systematically identify independent risk factors and develop an individualized risk prediction model. Surgical approach was included as a candidate predictor to quantify its independent contribution to postoperative recovery, rather than to test superiority between surgical modalities.

Patients were dichotomized into the prolonged-stay group (≥ median value) and non-prolonged-stay group (< median value), using the cohort-wide median of postoperative hospital stay derived from the PSM-matched population as the cut-off threshold.

Candidate predictors that were subjected to analysis included surgical approach, age, sex, body mass index, preoperative serum albumin, preoperative hemoglobin, neutrophil-to-lymphocyte ratio, maximum tumor diameter, Lauren classification, histological differentiation, N-stage, intraoperative blood loss, and operative time.

The prediction model was evaluated in terms of its power in discrimination (receiver operating characteristic [ROC] curve, area under the curve [AUC]), calibration (calibration plots with bootstrap internal validation), clinical utility (decision curve analysis), and model interpretability (SHapley Additive exPlanations [SHAP] algorithm). A nomogram was constructed based on regression coefficients to enable rapid quantitative assessment of individual patient risk.

Secondary Analysis: Effect Estimates of Surgical Approach on Perioperative Outcomes (Supporting Analysis)

This auxiliary analysis addressed the primary objective by deciphering the univariable associations of surgical approach with perioperative safety, postoperative recovery, and oncological radicality. It provided contextual background for interpreting the surgical-approach predictor within the primary risk prediction model and did not formally test superiority hypotheses for either surgical technique.

Perioperative safety endpoints included operative time, incision length, intraoperative blood loss, 30-day postoperative complication rate, and distribution of Clavien–Dindo grades.

Postoperative recovery endpoints included time to abdominal drain removal and total hospital stay.

Oncological radicality endpoints encompassed total number of retrieved lymph nodes, number of positive lymph nodes, and distribution of postoperative N-stage.

Exploratory Analysis: Effect Modification by Lauren Classification (Hypothesis-Generating Analysis)

Stratified analyses were performed across intestinal, diffuse, and mixed Lauren subtypes to evaluate associations between surgical approach and each endpoint. Regression models with multiplicative interaction terms were fitted to examine whether Lauren classification modified the relationship between surgical approach and postoperative recovery outcomes. This was a pre-specified, purely exploratory analysis—not designed to test surgical superiority, nor to confirm the predictive utility of Lauren classification for clinical decision-making. It aimed to detect poten-

tial signals of effect heterogeneity and generate preliminary hypotheses for future prospective confirmatory studies. No definitive clinical guidance regarding surgical approach selection by Lauren subtype was intended or should be inferred from these analyses.

Statistical Analysis

The statistical analyses utilized in this study were selected according to the predefined analytical framework consisting of three sequential objectives: (1) identifying independent predictors of prolonged postoperative hospital stay and developing an individualized risk prediction model as the primary objective; (2) comparing perioperative and oncological outcomes between surgical approaches to provide clinical context for interpreting model predictors as a secondary analysis; and (3) exploring whether Lauren classification modified the association between surgical approach and short-term outcomes as a hypothesis-generating analysis. Accordingly, statistical methods were applied according to each research question rather than as independent comparisons.

Baseline Covariate Description and Intergroup Balancing (Shared Methodological Foundation)

This section forms the shared methodological basis for all subsequent analyses. Its core objectives are to describe the baseline profile of the study cohort and to construct a balanced comparison population to minimize treatment-selection bias. The distribution of continuous variables was assessed using the Shapiro–Wilk test. Continuous variables that conform to a normal distribution were expressed as mean ± standard deviation (SD) and compared using independent-samples *t*-tests. Non-normally distributed continuous variables were presented as median (interquartile range) [M (P25, P75)] and analyzed using the Mann–Whitney *U* test. Categorical variables were reported as numbers (percentages) [n (%)], with comparisons performed using the chi-square test or Fisher's exact test when appropriate. Ordinal variables were analyzed using the Mann–Whitney *U* test.

Baseline balance was assessed using standardized mean differences (SMDs), with an SMD <0.1 indicating adequate balance. Hypothesis-testing *p*-values were not used for balance evaluation. Analyses were conducted in both the original and propensity score–matched cohorts, with the propensity score–matched cohort serving as the primary-analysis population.

To minimize treatment-selection bias, PSM was performed using 12 preoperative covariates potentially associated with surgical approach and outcomes: age, sex, BMI, preoperative CEA, CA19-9, hemoglobin, albumin, NLR, tumor location, maximum tumor diameter, histological differentiation, and Lauren classification. A logistic regression model was used to estimate propensity scores. One-to-one nearest-neighbor matching without replacement was performed with a caliper of 0.05 standard deviations of the logit-transformed propensity score, restricted to the region of common support.

Primary Analysis: Risk Factor Screening and Prediction Model Development for Prolonged Postoperative Hospital Stay

The primary analysis addresses the core research question: which factors are independently associated with prolonged postoperative hospital stay, and can a clinically practical individualized risk prediction model be constructed? We adopted a two-stage strategy: first identify independent predictors via regression, then build and comprehensively validate the prediction model. All primary analyses were performed in the propensity score–matched cohort. Univariable logistic regression was performed with prolonged postoperative hospitalization as the outcome, and variables with $p < 0.10$ were entered into multivariable binary logistic regression (Enter method). Independent predictors were reported with odds ratios (ORs) and 95% confidence intervals (CIs).

A prediction model was developed based on independent predictors and evaluated for discrimination, calibration, clinical utility, and interpretability. Discrimination was assessed using ROC curves and AUC values with 95% CIs. Calibration was evaluated using calibration curves with bootstrap internal validation (1000 resamples). Clinical utility was assessed by decision curve analysis (DCA). SHAP analysis was performed to quantify feature contributions and directions of effects. A nomogram was constructed based on regression coefficients for individualized risk estimation.

Statistical Methods for Secondary Analysis: Inter-Group Comparison of Perioperative and Oncopathological Outcomes

The secondary analysis provides clinical context for interpreting the primary findings by comparing perioperative safety, postoperative recovery, and oncological radicality between the two surgical approaches. This comparative analysis offers mechanistic evidence to explain why surgical approach acts as an independent predictor of prolonged hospitalization. Within the propensity score–matched cohort, indices of perioperative safety, recovery trajectory, and oncological radicality were compared between the laparoscopic and open surgery groups. These comparisons characterize the real-world performance of each procedure in our cohort and deliver complementary support for interpreting the surgical approach variable in the primary risk prediction model.

Exploratory Analysis: Subgroup and Interaction Testing for Lauren Classification Effect Modification

Within the propensity score–matched cohort, subgroup outcome comparisons were conducted with Lauren histotype stratification. Full-cohort regression models incorporat-

ing surgical approach, Lauren classification, and their multiplicative interaction term were constructed to test effect modification. Consistent with its strictly exploratory, hypothesis-generating purpose, this analysis was not powered to confirm definitive subgroup effects, and its findings do not provide a basis for tailoring surgical approach according to Lauren classification in clinical practice. This pre-specified exploratory analysis was not intended to test surgical superiority; it sought potential biological heterogeneity to inform future prospective investigations.

Statistical Thresholds and Software

All tests were two-sided, with $\alpha = 0.05$ and $p < 0.05$ considered statistically significant. Analyses were performed using SPSS version 26.0 (IBM Corp., Armonk, NY, USA) and R version 4.3.1 (R Foundation for Statistical Computing, Vienna, Austria, MatchIt, rms, and shapviz packages).

Results

Baseline and Clinicopathological Characteristics

A total of 302 patients with pT4a gastric adenocarcinoma who met the inclusion criteria were included in the final analysis, with 149 patients in the open surgery group and 153 in the laparoscopic surgery group. Baseline and clinicopathological characteristics of the original cohort are summarized in Table 1.

No significant differences were observed between the two groups in age, sex, or BMI (all $p > 0.05$). Tumor-related variables, including tumor location, gross type, histological grade, Lauren classification, and maximum tumor diameter, were also comparable between the two groups (all $p > 0.05$). Regarding preoperative laboratory and inflammatory markers, no significant differences were observed in CEA, CA19-9, hemoglobin, platelet count, monocyte level, PL%R, or LMR (all $p > 0.05$). However, the laparoscopic surgery group showed significantly lower neutrophil percentage and NLR compared with the open surgery group (both $p < 0.05$). Serum albumin and lymphocyte percentage showed borderline differences ($p = 0.090$ and $p = 0.051$, respectively).

After 1:1 nearest-neighbor propensity score matching, 124 patients were included in each group (total $n = 248$). The matched cohort included 12 baseline covariates (age, sex, BMI, CEA, CA19-9, tumor size, hemoglobin, albumin, NLR, tumor location, histological grade, and Lauren classification), with a caliper width of 0.05 SD of the logit-transformed propensity score and restriction to the common support region.

In the matched cohort (Table 2), all demographic, clinicopathological, nutritional, and inflammatory variables were well-balanced between the two groups (all $p > 0.05$). All SMDs were <0.1, confirming excellent covariate balance and effective control of selection bias (Fig. 1A,B). These results support the validity of subsequent comparative and subgroup analyses.

Screening of Independent Risk Factors for Prolonged Postoperative Hospital Stay (Baseline Analysis for Prediction Model Development)

This section describes the primary confirmatory analysis designed to identify independent predictors of prolonged postoperative hospital stay among patients with pT4a gastric cancer, which served as variable inputs for the development of the risk prediction model. Postoperative hospital stay represents a composite endpoint reflecting perioperative recovery quality, and correlates closely with postoperative complication risk, nosocomial infection, healthcare resource consumption and patient-related economic burden. Using the propensity score–matched cohort, patients were dichotomized into the prolonged-stay group (≥ cohort median postoperative hospital stay) and non-prolonged-stay group (< cohort median). Univariable and multivariable binary logistic regression analyses were performed to screen for independent risk factors for model selection.

Univariable regression results are presented in Table 3. Variables with $p < 0.10$ were entered into the multivariable model, including surgical approach, histological differentiation, N stage, intraoperative blood loss, and NLR. Univariable analysis showed that laparoscopic surgery, lower histological differentiation, and earlier N stage were associated with a reduced risk of prolonged hospitalization, whereas increased intraoperative blood loss and elevated NLR were associated with increased risk. Other variables, including sex, tumor location, gross tumor type, Lauren classification, age, BMI, preoperative CEA, CA19-9, operative time, maximum tumor diameter, hemoglobin, and albumin, were not significantly associated with prolonged hospitalization (all $p > 0.10$).

After adjustment for confounders, multivariable binary logistic regression analysis (Enter method) identified laparoscopic surgery as an independent protective factor against prolonged postoperative hospitalization (Table 4). Compared with open surgery, laparoscopic surgery was associated with a lower risk of prolonged hospitalization (OR = 0.47, 95% CI 0.27–0.82, $p = 0.008$). Histological differentiation was also independently associated with hospitalization duration: compared with low-to-moderate differentiation, poor differentiation (OR = 0.51, 95% CI 0.27–0.95, $p = 0.035$) and moderate-to-high differentiation (OR = 0.23, 95% CI 0.07–0.73, $p = 0.012$) were protective factors. Regarding N stage, compared with N0 stage, N1 (OR = 0.41, 95% CI 0.17–0.99, $p = 0.049$) and N3a stages (OR = 0.22, 95% CI 0.09–0.54, $p < 0.001$) were associated with a lower risk of prolonged hospitalization. Increased intraoperative blood loss remained an independent risk factor (OR = 1.01, 95% CI 1.01–1.01, $p = 0.026$). NLR did not retain statistical significance after multivariable adjustment ($p = 0.149$). Independent predictors identified after multivariable adjustment, such as surgical approach, histological differentiation, N-stage, and intraoperative blood loss, together with NLR, which showed strong associations in

Table 1. Baseline and clinicopathological characteristics of the original cohort.

Variable	Open surgery group (n = 149)	Laparoscopic surgery group (n = 153)	Statistic	p	SMD
Age (years), median (Q_1, Q_3)	62.00 (55.00, 69.00)	64.00 (57.00, 68.00)	$Z = -0.561$	0.575	0.056
BMI (kg/m^2), median (Q_1, Q_3)	22.84 (20.57, 24.93)	22.49 (20.20, 25.10)	$Z = -0.243$	0.808	0.005
CEA, median (Q_1, Q_3)	2.16 (1.42, 4.35)	1.95 (1.45, 3.44)	$Z = -0.947$	0.344	−0.093
CA19-9, median (Q_1, Q_3)	7.63 (4.22, 22.10)	7.80 (4.37, 19.90)	$Z = -0.237$	0.813	−0.259
Tumor maximum diameter, median (Q_1, Q_3)	6.00 (4.00, 7.00)	5.00 (4.00, 7.00)	$Z = -1.498$	0.134	−0.176
Hemoglobin, median (Q_1, Q_3)	109.00 (95.00, 122.00)	109.00 (92.00, 125.00)	$Z = -0.183$	0.855	0.076
Albumin, median (Q_1, Q_3)	28.75 (25.40, 31.77)	29.21 (26.80, 31.90)	$Z = -1.693$	0.090	0.086
Neutrophils, median (Q_1, Q_3)	81.70 (76.10, 88.10)	81.40 (73.42, 85.20)	$Z = -2.093$	0.036	−0.223
Lymphocytes, median (Q_1, Q_3)	9.50 (6.00, 13.40)	10.20 (7.20, 14.40)	$Z = -1.951$	0.051	0.187
Platelets, median (Q_1, Q_3)	179.00 (146.00, 230.00)	183.00 (141.00, 233.00)	$Z = -0.010$	0.992	0.052
Monocytes, median (Q_1, Q_3)	6.70 (5.00, 9.00)	6.90 (5.20, 8.60)	$Z = -0.385$	0.700	0.078
NLR, median (Q_1, Q_3)	8.50 (5.74, 14.32)	7.75 (5.17, 11.49)	$Z = -1.984$	0.047	−0.224
PL%R, median (Q_1, Q_3)	19.56 (11.97, 32.62)	15.82 (11.94, 25.78)	$Z = -1.753$	0.080	−0.061
LMR, median (Q_1, Q_3)	1.48 (0.91, 2.06)	1.58 (1.07, 2.21)	$Z = -1.646$	0.100	0.154
Sex, n (%)			$\chi^2 = 0.205$	0.651	
Male	120 (80.54)	120 (78.43)			−0.051
Female	29 (19.46)	33 (21.57)			0.051
Tumor location, n (%)			$\chi^2 = 3.807$	0.433	
Cardia	54 (36.24)	44 (28.76)			−0.165
Fundus	3 (2.01)	5 (3.27)			0.071
Antrum	15 (10.07)	13 (8.50)			−0.056
Angulus	5 (3.36)	10 (6.54)			0.129
Body	72 (48.32)	81 (52.94)			0.093
Gross type, n (%)			$\chi^2 = 0.545$	0.460	
Ulcerative	124 (83.22)	132 (86.27)			0.089
Protuberant	25 (16.78)	21 (13.73)			−0.089
Histological grade, n (%)			$\chi^2 = 3.313$	0.507	
Moderately-poorly differentiated	53 (35.57)	50 (32.68)			−0.062
Poorly differentiated	70 (46.98)	69 (45.10)			−0.038
Well differentiated	4 (2.68)	2 (1.31)			−0.121
Moderately-well differentiated	13 (8.72)	15 (9.80)			0.036
Moderately differentiated	9 (6.04)	17 (11.11)			0.161
Lauren classification, n (%)			$\chi^2 = 1.815$	0.404	
Intestinal type	10 (6.71)	17 (11.11)			0.14
Mixed type	96 (64.43)	95 (62.09)			−0.048
Diffuse type	43 (28.86)	41 (26.80)			−0.047

Abbreviations: BMI, body mass index; CA19-9, carbohydrate antigen 19-9; CEA, carcinoembryonic antigen; LMR, lymphocyte-to-monocyte ratio; NLR, neutrophil-to-lymphocyte ratio; PL%R, platelet-to-lymphocyte percentage ratio; SMD, standardized mean difference.

univariable analysis, constituted the candidate variable set for the subsequent prediction model development.

Development and Performance Evaluation of the Prediction Model for Prolonged Postoperative Hospital Stay (Key Study Findings)

An individualized risk prediction model for prolonged postoperative hospital stay was developed using independent predictors to support clinical risk stratification. Model performance was comprehensively evaluated across four dimensions: discrimination, interpretability, calibration, and clinical utility.

The discriminative ability was assessed using ROC analysis (Fig. 2A). The model achieved an AUC of 0.73 (95% CI 0.67–0.79), which indicates moderate predictive performance for identifying patients at high risk of prolonged hospitalization after pT4a gastric cancer surgery.

SHAP analysis was performed to quantify the contribution of individual variables to model prediction (Fig. 2B). The ranking of feature importance was as follows: N stage > surgical approach > histological differentiation > intraoperative blood loss > NLR. N stage showed the highest mean absolute SHAP value, representing the strongest contributor to model prediction, followed by surgical approach, which independently influenced postoperative hospitalization duration.

Table 2. Comparison of baseline clinicopathological and tumor characteristics in the propensity score-matched cohort.

Variable	Open surgery group (n = 124)	Laparoscopic surgery group (n = 124)	Statistic	p	SMD
Age (years), median (Q_1, Q_3)	62.00 (54.00, 69.00)	64.00 (57.00, 68.00)	$Z = -0.234$	0.815	0.043
BMI (kg/m^2), median (Q_1, Q_3)	22.85 (20.75, 24.98)	22.59 (20.28, 25.39)	$Z = -0.189$	0.850	0.005
CEA, median (Q_1, Q_3)	2.00 (1.36, 3.96)	1.94 (1.45, 3.36)	$Z = -0.260$	0.795	−0.036
CA19-9, median (Q_1, Q_3)	7.96 (4.36, 20.08)	8.23 (4.40, 20.82)	$Z = -0.401$	0.688	−0.044
Tumor maximum diameter, median (Q_1, Q_3)	5.50 (4.00, 7.00)	5.00 (4.00, 7.00)	$Z = -0.361$	0.718	−0.022
Hemoglobin, median (Q_1, Q_3)	109.00 (95.00, 123.00)	109.00 (92.00, 122.75)	$Z = -0.019$	0.985	0.01
Albumin, median (Q_1, Q_3)	28.85 (25.65, 31.70)	29.10 (26.60, 31.95)	$Z = -1.133$	0.257	0.048
Neutrophils, median (Q_1, Q_3)	80.50 (75.45, 86.85)	81.45 (74.05, 85.20)	$Z = -1.045$	0.296	−0.095
Lymphocytes, median (Q_1, Q_3)	9.95 (6.12, 13.55)	10.10 (7.20, 14.10)	$Z = -1.136$	0.256	0.093
Platelets, median (Q_1, Q_3)	180.50 (146.00, 237.75)	183.50 (140.50, 233.00)	$Z = -0.137$	0.891	−0.060
Monocytes, median (Q_1, Q_3)	6.80 (5.20, 9.20)	7.00 (5.20, 8.75)	$Z = -0.034$	0.973	−0.054
NLR, median (Q_1, Q_3)	8.19 (5.71, 13.91)	7.99 (5.19, 11.49)	$Z = -1.104$	0.270	−0.092
PL&R, median (Q_1, Q_3)	18.52 (10.67, 30.47)	16.61 (11.87, 25.68)	$Z = -1.036$	0.300	−0.094
LMR, median (Q_1, Q_3)	1.51 (0.93, 2.08)	1.56 (1.06, 2.20)	$Z = -1.137$	0.256	0.079
Sex, n (%)			$\chi^2 = 0.205$	0.651	
Male	97 (78.23)	94 (75.81)			−0.056
Female	27 (21.77)	30 (24.19)			0.056
Tumor location, n (%)			—	0.989	
Cardia	39 (31.45)	41 (33.06)			0.034
Fundus	3 (2.42)	3 (2.42)			0
Antrum	14 (11.29)	12 (9.68)			−0.055
Angulus	4 (3.23)	5 (4.03)			0.041
Body	64 (51.61)	63 (50.81)			−0.016
Gross type, n (%)			$\chi^2 = 0.574$	0.449	
Ulcerative	110 (88.71)	106 (85.48)			−0.092
Protuberant	14 (11.29)	18 (14.52)			0.092
Histological grade, n (%)			$\chi^2 = 0.080$	0.999	
Moderately-poorly differentiated	42 (33.87)	44 (35.48)			0.034
Poorly differentiated	61 (49.19)	59 (47.58)			−0.032
Well differentiated	2 (1.61)	2 (1.61)			0
Moderately-well differentiated	10 (8.06)	10 (8.06)			0
Moderately differentiated	9 (7.26)	9 (7.26)			0
Lauren classification, n (%)			$\chi^2 = 0.065$	0.968	
Intestinal type	9 (7.26)	8 (6.45)			−0.033
Mixed type	79 (63.71)	80 (64.52)			0.017
Diffuse type	36 (29.03)	36 (29.03)			0

Model calibration was assessed using calibration curve analysis (Fig. 3A). Both the apparent calibration curve and bias-corrected curve derived from 1000 bootstrap resamples closely aligned with the ideal diagonal reference line, demonstrating strong concordance between model-predicted probabilities and observed real-world outcomes, with no substantial overfitting detected.

Clinical net benefit was evaluated using decision curve analysis (Fig. 3B). Across a broad threshold probability range of 0.1–0.7, the established prediction model yielded superior net clinical benefit relative to two reference strategies: universal intervention for all patients and no intervention for all patients. This finding suggests that the model may have potential clinical utility in perioperative risk stratification.

To facilitate individualized risk assessment, a nomogram incorporating five identified predictors, namely the surgical approach, histological differentiation, N stage, intraoperative blood loss, and NLR, was constructed (Fig. 4). By summing the points assigned to each variable, clinicians can estimate the probability of prolonged postoperative hospitalization for each individual. Because the model incorporates postoperative pathological variables (histological differentiation and N stage), it is intended for risk stratification during the postoperative recovery period after routine pathological confirmation (approximately postoperative days 3–5), rather than for preoperative surgical decision-making.

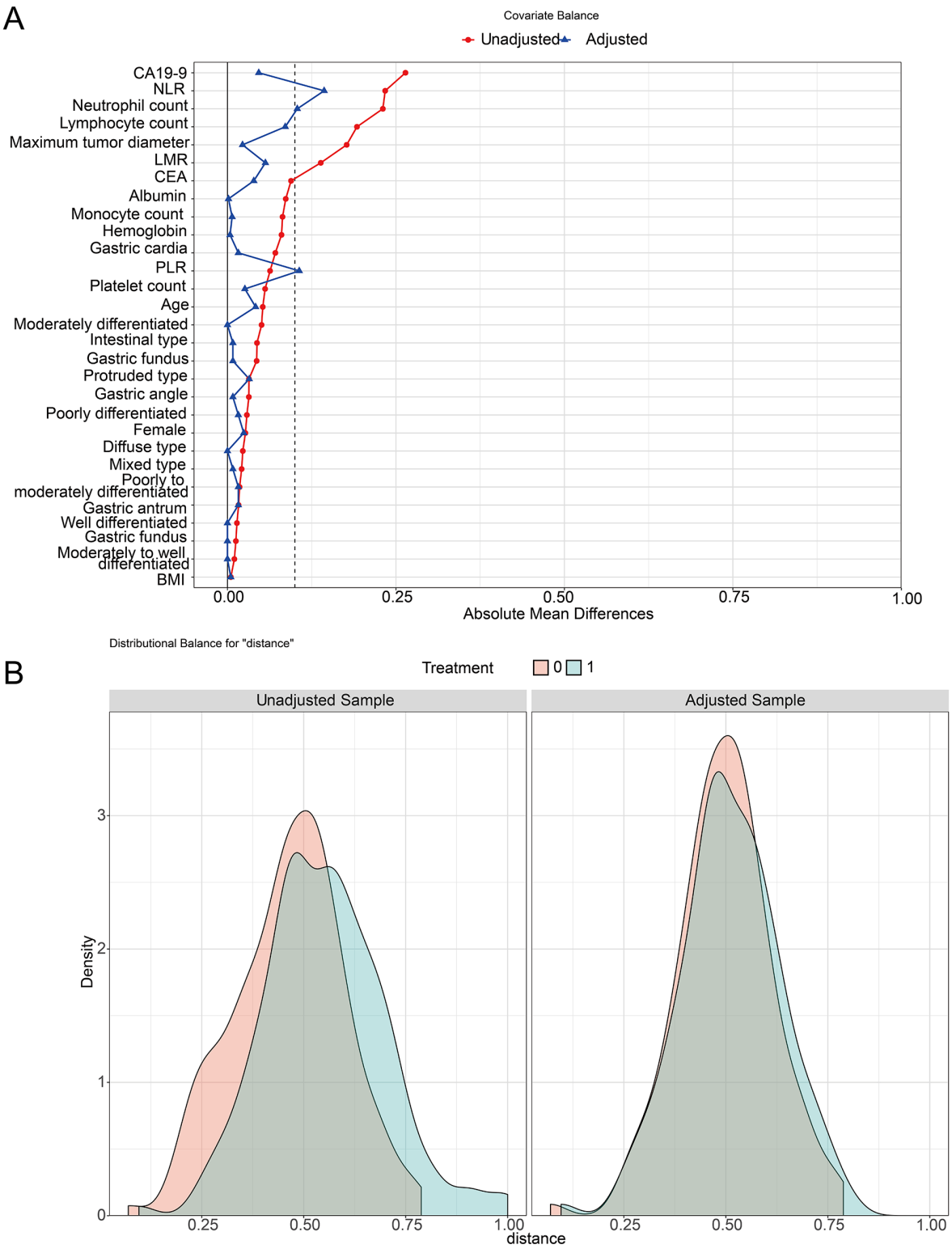

Fig. 1. Propensity score matching analysis. (A) Probability density plots of propensity scores before and after matching. (B) Standardized mean difference (SMD) plots of all covariates before and after matching.

Perioperative Clinical Outcomes and Postoperative Pathological Features (Supporting Interpretative Analysis)

In this section, the protective effect of laparoscopic surgery identified during the screening of independent risk factors was further evaluated. This auxiliary analysis was not intended as a standalone comparative effectiveness study between surgical approaches. Comparisons were performed in the propensity score–matched cohort consisting of 248 patients (Table 5).

Table 3. Univariate binary logistic regression for predictors of prolonged postoperative hospital stay.

Variables	β	S.E	*Z*	*p*	OR (95% CI)
Surgical strategy					
Open surgery	—	—	—	—	1.00 (Reference)
Laparoscopic surgery	−0.62	0.26	−2.40	0.016	0.54 (0.33–0.89)
Sex					
Male	—	—	—	—	1.00 (Reference)
Female	−0.48	0.31	−1.56	0.119	0.62 (0.34–1.13)
Tumor location					
Cardia	—	—	—	—	1.00 (Reference)
Fundus	0.74	0.89	0.83	0.406	2.10 (0.36–12.14)
Antrum	0.05	0.45	0.11	0.912	1.05 (0.43–2.55)
Angulus	0.27	0.71	0.39	0.699	1.31 (0.33–5.25)
Body	0.13	0.29	0.45	0.652	1.14 (0.65–1.99)
Gross tumor type					
Ulcerative	—	—	—	—	1.00 (Reference)
Protuberant	0.38	0.38	0.99	0.324	1.46 (0.69–3.11)
Histological grade					
Moderately-poorly differentiated	—	—	—	—	1.00 (Reference)
Poorly differentiated	−0.69	0.29	−2.39	0.017	0.50 (0.28–0.88)
Well differentiated	−1.62	1.18	−1.38	0.168	0.20 (0.02–1.98)
Moderately-well differentiated	−0.93	0.51	−1.83	0.068	0.40 (0.15–1.07)
Moderately differentiated	−0.52	0.52	−1.00	0.316	0.59 (0.21–1.65)
Lauren classification					
Intestinal type	—	—	—	—	1.00 (Reference)
Mixed type	0.44	0.52	0.86	0.39	1.56 (0.57–4.30)
Diffuse type	0.41	0.55	0.75	0.45	1.51 (0.52–4.41)
N stage (TNM)					
N0	—	—	—	—	1.00 (Reference)
N1	−0.83	0.42	−1.97	0.049	0.44 (0.19–0.99)
N2	−0.14	0.41	−0.34	0.735	0.87 (0.39–1.95)
N3a	−1.21	0.41	−2.95	0.003	0.30 (0.13–0.67)
N3b	0.08	0.5	0.16	0.87	1.09 (0.41–2.90)
Age	0.02	0.01	1.31	0.19	1.02 (0.99–1.04)
BMI	0.01	0.04	0.39	0.697	1.01 (0.94–1.09)
CEA	0.01	0.01	1.36	0.173	1.01 (1.00–1.03)
CA19-9	0	0	0.02	0.981	1.00 (1.00–1.00)
Operative duration	−0.05	0.07	−0.67	0.503	0.95 (0.83–1.10)
Intraoperative blood loss	0.01	0	2.27	0.023	1.01 (1.01–1.01)
Maximum tumor diameter	0.07	0.05	1.36	0.175	1.07 (0.97–1.19)
Hemoglobin	0	0.01	0.39	0.698	1.00 (0.99–1.01)
Albumin	−0.02	0.02	−1.04	0.299	0.98 (0.95–1.02)
NLR	0.05	0.02	2.49	0.013	1.05 (1.01–1.09)

Abbreviations: OR, odds ratio; CI, confidence interval; S.E, standard error; TNM, Tumor–Node–Metastasis.

Regarding perioperative safety and surgical trauma, laparoscopic surgery required a significantly longer operative time than open surgery [4.00 (4.00, 4.15) h vs. 3.50 (3.00, 4.00) h, $p < 0.001$]. However, the laparoscopic surgery group had significantly shorter incision length [6.00 (6.00, 8.00) cm vs. 16.00 (15.00, 17.00) cm, $p < 0.001$] and lower intraoperative blood loss [100.00 (100.00, 300.00) mL vs. 200.00 (100.00, 200.00) mL, $p = 0.013$], demonstrating clear advantages in terms of minimal invasiveness.

For postoperative recovery outcomes, the laparoscopic surgery group showed earlier abdominal drainage tube removal [9.00 (8.00, 11.00) d vs. 10.00 (9.00, 12.00) d, $p = 0.005$], shorter postoperative hospital stay [10.00 (9.00, 13.00) d vs. 11.00 (10.00, 14.00) d, $p = 0.008$], and shorter

Table 4. Multivariate binary logistic regression for independent predictors of prolonged postoperative hospital stay.

Variables	β	S.E	*Z*	*p*	OR (95% CI)
Intercept	0.87	0.5	1.73	0.083	2.38 (0.89–6.36)
Surgical strategy					
Open surgery	—	—	—	—	1.00 (Reference)
Laparoscopic surgery	−0.76	0.29	−2.67	0.008	0.47 (0.27–0.82)
Histological grade					
Moderately-poorly differentiated	—	—	—	—	1.00 (Reference)
Poorly differentiated	−0.67	0.32	−2.11	0.035	0.51 (0.27–0.95)
Well differentiated	−2.11	1.25	−1.68	0.093	0.12 (0.01–1.42)
Moderately-well differentiated	−1.46	0.58	−2.50	0.012	0.23 (0.07–0.73)
Moderately differentiated	−0.36	0.58	−0.61	0.541	0.70 (0.22–2.19)
N stage (TNM)					
N0	—	—	—	—	1.00 (Reference)
N1	−0.90	0.46	−1.97	0.049	0.41 (0.17–0.99)
N2	−0.13	0.44	−0.30	0.766	0.88 (0.37–2.08)
N3a	−1.49	0.45	−3.33	<0.001	0.22 (0.09–0.54)
N3b	−0.04	0.55	−0.07	0.945	0.96 (0.33–2.80)
Intraoperative blood loss	0.01	0	2.23	0.026	1.01 (1.01–1.01)
NLR	0.03	0.02	1.44	0.149	1.03 (0.99–1.07)

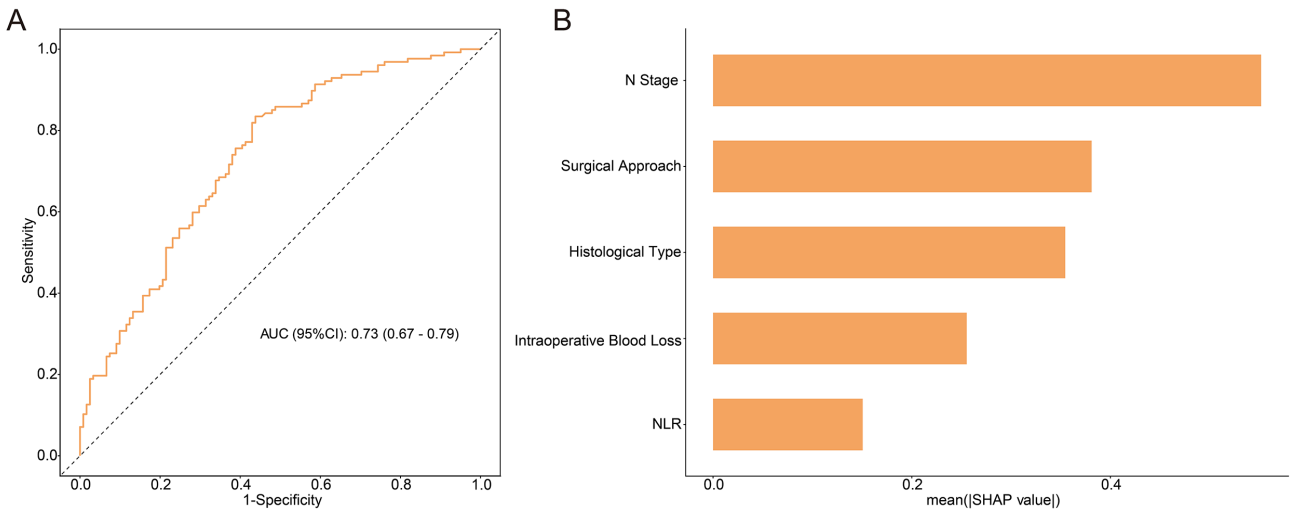

Fig. 2. Discriminative performance and feature importance of the prediction model for prolonged postoperative hospital stay. (A) Receiver operating characteristic (ROC) curve evaluating model discrimination. (B) SHapley Additive exPlanations (SHAP) feature importance plot. Mean absolute SHAP values quantify the average marginal contribution of each predictor to model outputs; variables are sorted in descending order of predictive weight. Abbreviations: AUC, area under the ROC curve.

total hospital stay [17.00 (14.00, 20.00) d vs. 18.00 (16.00, 23.00) d, $p = 0.015$] compared with open surgery.

Regarding oncological radicality, no significant differences were observed between groups in total retrieved lymph nodes [22.00 (16.75, 30.00) vs. 23.00 (19.00, 29.25), $p = 0.287$], metastatic lymph nodes [4.00 (1.00, 10.00) vs. 4.00 (1.00, 9.00), $p = 1.000$], or postoperative N stage distribution ($p = 0.575$). These findings suggest that laparoscopic surgery achieved comparable D2 lymphadenectomy to open surgery in this cohort, with no significant differences observed in lymph node retrieval and pathological N-stage outcomes between the two approaches.

Exploration of Subgroup Interaction Effects Stratified by Lauren Subtypes (Exploratory Analysis)

This exploratory analysis was not one of the main outcomes that the study was primarily designed or powered to assess, and definitive clinical conclusions cannot be drawn from these results. It preliminarily assessed potential effect modification by Lauren histotype and generated hypotheses for future large-scale, precision-oriented investigations.

Further stratified analyses were performed within the propensity score–matched cohort. First, overall perioperative and pathological characteristics were compared among the Lauren subtypes (Table 6). Kruskal–Wallis H tests

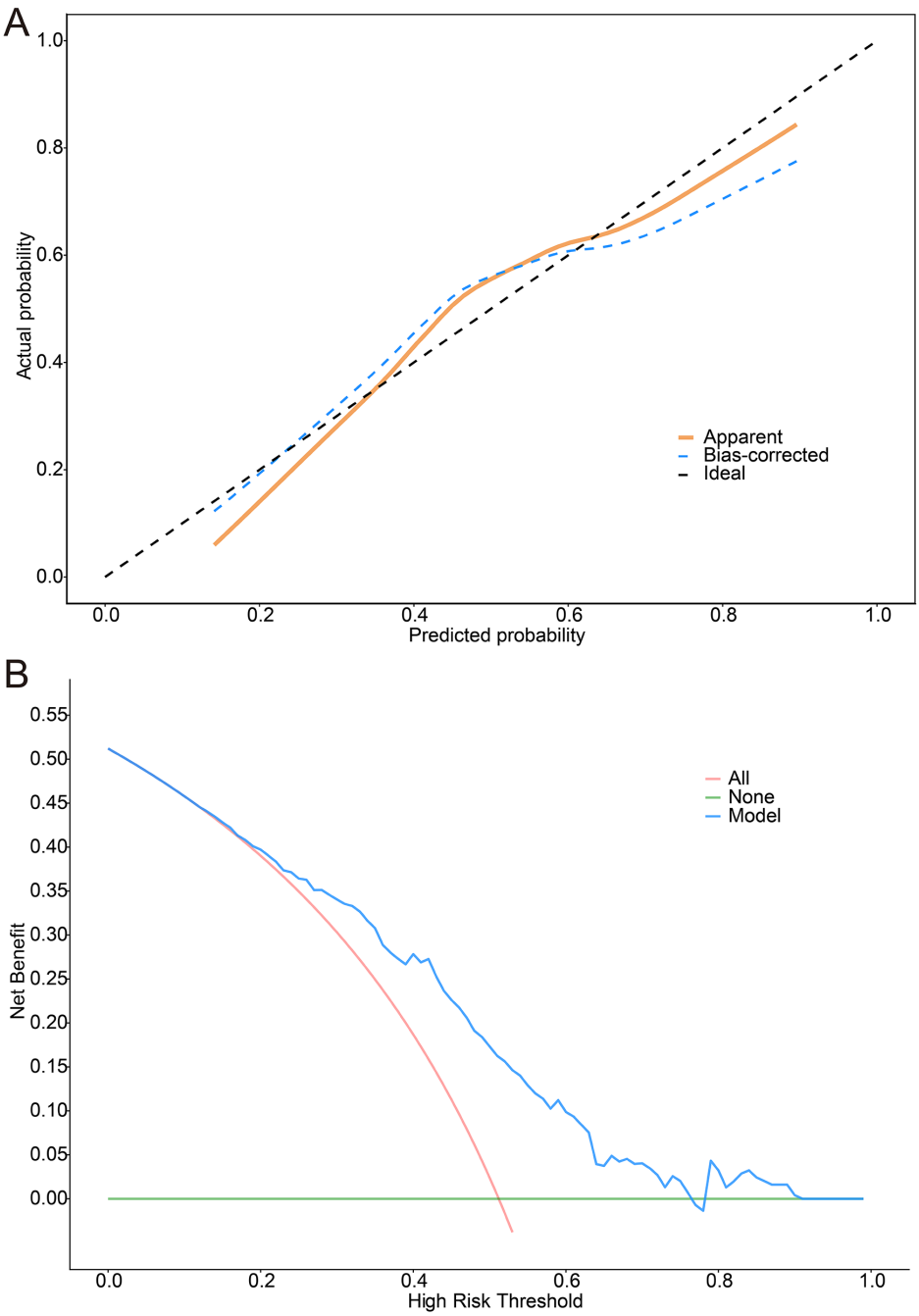

Fig. 3. Calibration and clinical utility assessment of the prediction model for prolonged postoperative hospital stay. (A) Calibration plot. Orange solid line = apparent calibration curve; blue dashed line = bias-corrected curve after 1000 bootstrap internal validations; black dashed line = ideal perfect calibration diagonal. Closer alignment with the diagonal signifies better agreement between predicted and observed event probabilities. (B) Decision curve analysis. X-axis = risk threshold probability; Y-axis = net clinical benefit. Blue solid line = current prediction model; red solid line = strategy of intervening on all patients; green solid line = strategy of intervening on no patients.

showed no significant differences among intestinal, mixed, and diffuse subtypes in operative time, incision length, intraoperative blood loss, total hospital stay, time to abdominal drainage tube removal, postoperative hospital stay, total retrieved lymph nodes, or metastatic lymph nodes (all $p > 0.05$). These findings indicated that, within this cohort, no significant differences in perioperative recovery profiles or baseline tumor burden were observed among the three Lauren subtypes.

Subsequently, binary outcomes were defined according to the overall cohort median values of each parameter, and laparoscopic versus open surgery outcomes were compared within each Lauren subtype. Multiplicative interaction effects were further evaluated (Table 7).

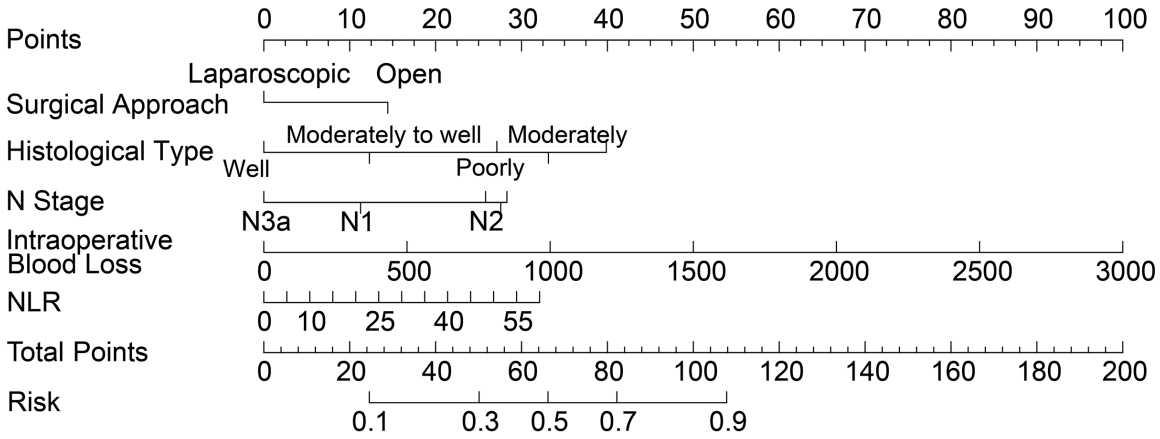

Fig. 4. Nomogram for predicting prolonged postoperative hospital stay in patients with pT4a gastric cancer. For each patient, draw a vertical line from each covariate value to the top "Points" axis to retrieve individual predictor scores. Sum all five component scores to calculate the total point value; draw a vertical line downward from the "Total Points" scale to read the personalized probability of prolonged postoperative hospital stay.

Table 5. Comparison of perioperative clinical outcomes and postoperative pathological characteristics in the propensity score–matched cohort.

Variable	Total cohort (n = 248)	Open surgery group (n = 124)	Laparoscopic surgery group (n = 124)	Statistic	p
Perioperative clinical outcomes					
Operative duration (h), median (Q_1, Q_3)	4.00 (3.20, 4.00)	3.50 (3.00, 4.00)	4.00 (4.00, 4.15)	$Z = -6.50$	<0.001
Incision length (cm), median (Q_1, Q_3)	10.00 (6.00, 16.00)	16.00 (15.00, 17.00)	6.00 (6.00, 8.00)	$Z = -12.10$	<0.001
Intraoperative blood loss (mL), median (Q_1, Q_3)	200.00 (100.00, 200.00)	200.00 (100.00, 200.00)	100.00 (100.00, 300.00)	$Z = -2.48$	0.013
Total hospital stay (d), median (Q_1, Q_3)	18.00 (15.00, 21.00)	18.00 (16.00, 23.00)	17.00 (14.00, 20.00)	$Z = -2.44$	0.015
Time to abdominal drain removal (d), median (Q_1, Q_3)	10.00 (8.00, 11.00)	10.00 (9.00, 12.00)	9.00 (8.00, 11.00)	$Z = -2.81$	0.005
Postoperative hospital stay (d), median (Q_1, Q_3)	11.00 (9.00, 13.00)	11.00 (10.00, 14.00)	10.00 (9.00, 13.00)	$Z = -2.64$	0.008
Postoperative pathological characteristics					
Total number of harvested lymph nodes, median (Q_1, Q_3)	23.00 (18.00, 30.00)	23.00 (19.00, 29.25)	22.00 (16.75, 30.00)	$Z = -1.06$	0.287
Number of metastatic lymph nodes, median (Q_1, Q_3)	4.00 (1.00, 10.00)	4.00 (1.00, 9.00)	4.00 (1.00, 10.00)	$Z = 0.00$	1.000
N stage, n (%)				$\chi^2 = 2.90$	0.575
N0	44 (17.74)	22 (17.74)	22 (17.74)		
N1	53 (21.37)	24 (19.35)	29 (23.39)		
N2	58 (23.39)	29 (23.39)	29 (23.39)		
N3a	64 (25.81)	37 (29.84)	27 (21.77)		
N3b	29 (11.69)	12 (9.68)	17 (13.71)		

For surgical trauma-related outcomes, the overall analysis showed that laparoscopic surgery was associated with a significantly increased risk of prolonged operative time compared with open surgery (OR = 7.45, 95% CI 4.16–13.35, $p < 0.001$), but significantly reduced risks of longer incision length and increased intraoperative blood loss (both $p < 0.001$). Similar trends were observed across intestinal, mixed, and diffuse subgroups, with no significant interaction effects detected (operative time: $p_{interaction} = 0.314$; incision length: $p_{interaction} = 0.450$; intraoperative blood loss: $p_{interaction} = 0.108$). Given the limited subgroup sample sizes, these analyses lacked sufficient statistical power to determine whether Lauren classification modified the effects of surgical approach on surgical trauma–related outcomes.

Table 6. Subgroup comparison of clinical outcomes stratified by Lauren classification in the propensity score–matched cohort.

Variable	Total (n = 248)	Intestinal type (n = 17)	Mixed type (n = 159)	Diffuse type (n = 72)	Statistic	p
Operative duration, median (Q_1, Q_3)	4.00 (3.20, 4.00)	4.00 (3.50, 4.00)	4.00 (3.50, 4.00)	4.00 (3.00, 4.00)	χ^2 = 1.02#	0.599
Incision length, median (Q_1, Q_3)	10.00 (6.00, 16.00)	12.00 (8.00, 15.00)	10.00 (6.00, 16.00)	10.00 (6.00, 16.00)	χ^2 = 0.24#	0.888
Intraoperative blood loss, median (Q_1, Q_3)	200.00 (100.00, 200.00)	200.00 (100.00, 200.00)	200.00 (100.00, 300.00)	150.00 (100.00, 200.00)	χ^2 = 2.31#	0.315
Total hospital stay, median (Q_1, Q_3)	18.00 (15.00, 21.00)	16.00 (15.00, 17.00)	18.00 (15.00, 21.00)	18.00 (15.00, 23.25)	χ^2 = 2.53#	0.283
Total harvested lymph nodes, median (Q_1, Q_3)	23.00 (18.00, 30.00)	22.00 (17.00, 33.00)	23.00 (17.50, 30.00)	23.00 (18.00, 30.00)	χ^2 = 0.26#	0.876
Number of metastatic lymph nodes, median (Q_1, Q_3)	4.00 (1.00, 10.00)	3.00 (0.00, 6.00)	4.00 (1.00, 9.00)	4.50 (1.75, 11.00)	χ^2 = 1.68#	0.431
Time to abdominal drain removal, median (Q_1, Q_3)	10.00 (8.00, 11.00)	9.00 (7.00, 10.00)	10.00 (8.50, 11.00)	10.00 (8.00, 13.00)	χ^2 = 3.49#	0.175
Postoperative hospital stay, median (Q_1, Q_3)	11.00 (9.00, 13.00)	10.00 (9.00, 11.00)	11.00 (9.00, 13.00)	11.00 (9.00, 15.25)	χ^2 = 1.30#	0.522

Data are presented as median (Q_1, Q_3). #Kruskal–Wallis test was used for comparisons among three Lauren classification groups.

Regarding postoperative recovery and oncological outcomes, laparoscopic surgery was associated with a lower risk of prolonged postoperative hospitalization in the overall cohort (OR = 0.54, 95% CI 0.33–0.89, p = 0.016). Subgroup analysis showed a more pronounced protective effect in the intestinal subtype (OR = 0.07, 95% CI 0.01–0.88, p = 0.039), whereas the mixed and diffuse subgroups showed similar effect directions without statistical significance. No significant interaction was observed between Lauren classification and surgical approach ($p_{interaction}$ = 0.151).

For oncological outcomes, no significant differences were observed between laparoscopic and open surgery in the overall cohort regarding total retrieved lymph nodes or metastatic lymph nodes (both $p > 0.05$). Among the subgroups, only the mixed subtype showed a slightly lower odds of achieving high total harvested lymph nodes in the laparoscopic group (OR = 0.50, p = 0.032), whereas no significant differences were found in other subgroups. Interaction tests were not statistically significant (all $p_{interaction} > 0.05$). Due to limited subgroup sizes, these findings indicate only that no significant stratifying effect was detected in this cohort and do not establish equivalent oncological radicality between surgical approaches across different Lauren subtypes.

It should be noted that interaction analyses generally require substantially larger sample sizes than analyses of main effects, often up to four times larger, to detect effects of comparable magnitude. In this study, subgroup sample sizes were limited, particularly in the intestinal subtype (n = 17), resulting in insufficient statistical power to detect weak-to-moderate effect modifications. Therefore, all subgroup and interaction analyses should be treated as exploratory. The absence of statistical significance does not exclude the possibility of a true effect modification, and the potential role of Lauren classification in modifying surgical outcomes requires validation in larger multicenter studies.

Discussion

Postoperative length of hospital stay is an important indicator of perioperative recovery quality and healthcare resource utilization in gastrointestinal surgery, reflecting, to some extent, surgical trauma, postoperative complications, and patient recovery status [16]. Previous studies have demonstrated that postoperative complications represent the primary determinant of prolonged hospitalization, and extended length of hospital stay (LOS) is associated not only with an increased risk of in-hospital adverse events but also with greater healthcare resource consumption and financial burden on patients [17,18]. Analyses were performed following a hierarchical primary-secondary-exploratory design. The primary aim was to identify independent predictors of prolonged postoperative hospital stay and to develop and validate an individualized risk stratification model. Comparisons of perioperative and pathological outcomes between laparoscopic and open gastrectomy served as secondary supporting analyses to characterize the clinical effect of surgical approach as a critical modifiable variable. Subgroup and interaction analyses according to the Lauren classification were purely exploratory, aiming to detect potential effect-modifying signals and generate hypotheses for further research.

Multivariable logistic regression identified four independent predictors of prolonged postoperative hospital stay, namely the surgical approach, histological differentiation, N-stage, and intraoperative blood loss. Among these, laparoscopic surgery emerged as an independent protective factor, reducing the risk of prolonged hospitalization by 53% after adjustment for potential confounders. This find-

Table 7. Subgroup analyses of dichotomized endpoints stratified by Lauren classification (laparoscopic vs. open surgery).

Endpoint and subgroup	Total *n* (%)	Open surgery (events/total)	Laparoscopic surgery (events/total)	OR (95% CI)	*p*	$p_{interaction}$
Prolonged operative duration (≥ median)						0.314
Overall cohort	248 (100.0)	46/124	101/124	7.45 (4.16–13.35)	<0.001	
Lauren classification–stratified cohort						
Intestinal type	17 (6.9)	3/9	7/8	14.00 (1.14–172.64)	0.039	
Mixed type	159 (64.1)	30/79	69/80	10.25 (4.68–22.43)	<0.001	
Diffuse type	72 (29.0)	13/36	25/36	4.02 (1.51–10.74)	0.006	
Extended incision length (≥ median)						0.450
Overall cohort	248 (100.0)	114/124	26/124	0.02 (0.01–0.05)	<0.001	
Lauren classification–stratified cohort						
Intestinal type	17 (6.9)	8/9	3/8	0.08 (0.01–0.94)	0.044	
Mixed type	159 (64.1)	73/79	19/80	0.03 (0.01–0.07)	<0.001	
Diffuse type	72 (29.0)	33/36	4/36	0.01 (0.01–0.05)	<0.001	
Excessive intraoperative blood loss (≥ median)						0.108
Overall cohort	248 (100.0)	83/124	55/124	0.39 (0.24–0.66)	<0.001	
Lauren classification–stratified cohort						
Intestinal type	17 (6.9)	8/9	2/8	0.04 (0.01–0.57)	0.018	
Mixed type	159 (64.1)	53/79	41/80	0.52 (0.27–0.98)	0.043	
Diffuse type	72 (29.0)	22/36	12/36	0.32 (0.12–0.83)	0.02	
Prolonged postoperative hospital stay (≥ median)						0.151
Overall cohort	248 (100.0)	73/124	54/124	0.54 (0.33–0.89)	0.016	
Lauren classification–stratified cohort						
Intestinal type	17 (6.9)	6/9	1/8	0.07 (0.01–0.88)	0.039	
Mixed type	159 (64.1)	45/79	38/80	0.68 (0.37–1.28)	0.233	
Diffuse type	72 (29.0)	22/36	15/36	0.45 (0.18–1.17)	0.101	
High total harvested lymph nodes (≥ median)						0.463
Overall cohort	248 (100.0)	74/124	59/124	0.61 (0.37–1.01)	0.057	
Lauren classification–stratified cohort						
Intestinal type	17 (6.9)	5/9	3/8	0.48 (0.07–3.35)	0.459	
Mixed type	159 (64.1)	50/79	37/80	0.50 (0.26–0.94)	0.032	
Diffuse type	72 (29.0)	19/36	19/36	1.00 (0.40–2.52)	1	
High metastatic lymph node count (≥ median)						0.802
Overall cohort	248 (100.0)	67/124	67/124	1.00 (0.61–1.65)	1	
Lauren classification–stratified cohort						
Intestinal type	17 (6.9)	4/9	4/8	1.25 (0.19–8.44)	0.819	
Mixed type	159 (64.1)	44/79	42/80	0.88 (0.47–1.64)	0.686	
Diffuse type	72 (29.0)	19/36	21/36	1.25 (0.49–3.18)	0.635	

ing was highly consistent with the trend observed in univariate analyses and suggests that the recovery advantages of minimally invasive surgery exist independently of tumor burden, baseline nutritional status, and inflammatory conditions. The underlying mechanisms are likely related to reduced abdominal wall trauma, attenuated systemic inflammatory stress, and better preservation of enteric autonomic function [19,20]. Increased intraoperative blood loss was the only independent risk factor identified. Excessive blood loss may trigger systemic inflammatory response syndrome and disrupt coagulation–fibrinolysis homeostasis. Furthermore, some patients require perioperative blood transfusion, which has been shown to prolong hospitalization and impair postoperative immune function in patients with gastric cancer. These findings highlight a key modifiable target for perioperative management: the routine application of meticulous hemostatic techniques and advanced energy devices, together with perioperative blood conservation strategies in patients at high risk of bleeding, may effectively reduce the occurrence of prolonged length of hospital stay.

Compared with poorly-to-moderately differentiated tumors, both poorly differentiated and moderately-to-well differentiated tumors were associated with a lower risk of prolonged hospitalization. Likewise, patients with N1 and N3a disease exhibited a lower risk of prolonged length of

stay than those with N0 disease. These findings should not be interpreted as indicating faster recovery among patients with biologically more aggressive tumors. Rather, they are more likely attributable to systematic differences in clinical management. These unexpected findings may reflect residual confounding or unmeasured clinical factors and should therefore be interpreted cautiously. Patients with lower tumor burden may experience unexpected delays in recovery due to unrecognized comorbidities or underestimation of surgical complexity. This observation also reflects the unavoidable influence of unmeasured confounding inherent in retrospective studies. Although the NLR was significant in univariate analysis, its effect was attenuated after multivariable adjustment, suggesting that NLR may serve primarily as a surrogate marker of surgical stress and baseline inflammatory status rather than an independent driver of delayed postoperative recovery.

Based on these independent predictors, we established a risk prediction model for prolonged length of hospital stay. The risk prediction model developed in this study demonstrated an AUC of 0.73 (95% CI: 0.67–0.79), indicating acceptable discriminative performance despite its relatively limited number of predictors. Calibration plots and bootstrap internal validation demonstrated good agreement between predicted and observed outcomes, with no evidence of substantial overfitting. Decision curve analysis further confirmed stable clinical net benefit across a broad threshold probability range of 0.1–0.7. SHAP analysis identified N stage and surgical approach as the two most influential features, which represent the dimensions of tumor burden and surgical technique, respectively. These findings are highly consistent with clinical knowledge and further support the content validity of the model.

The principal potential value of our prediction model lies in enabling risk stratification during the mid-to-late postoperative period and serving as a baseline tool for future prospective interventional studies. Since postoperative pathological parameters are incorporated, the model applies only after conventional paraffin-embedded pathological reports become available, typically 3–5 days post-surgery. Individual probabilities calculated from the nomogram could theoretically stratify patients into high- and low-risk subgroups for prolonged hospitalization and inform tailored rehabilitation strategies. For instance, high-risk patients might be candidates for intensified interventions, including optimized drain management, enhanced nutritional support, more frequent inflammatory biomarker monitoring, and personalized discharge-follow-up protocols. Low-risk patients could represent a target population for enhanced recovery after surgery (ERAS) pathway refinement. Nevertheless, these management strategies remain theoretical inferences derived from risk stratification and have not been validated in the existing evidence. Prospective randomized controlled trials or stepped-wedge cluster-randomized trials are required for further validation.

Surgical approach acts as a key modifiable protective predictor within the model. Secondary comparative analyses of perioperative and pathological outcomes corroborated the recovery-related benefits and oncological safety of laparoscopic gastrectomy at the univariable level, providing clinical context for findings derived from multivariable analyses. Following propensity score matching (PSM), the laparoscopic surgery group exhibited significantly longer operative times but shorter incision lengths and lower intraoperative blood loss than the open surgery group. These findings are highly consistent with those reported in large-scale trials such as CLASS-01 and KLASS-02 [7,8]. However, these findings should be interpreted with caution because previous trials mainly included broader locally advanced gastric cancer populations and different surgical procedures, which may limit their direct applicability to patients with pT4a disease undergoing total gastrectomy. The longer operative duration is primarily attributable to the technical complexity of laparoscopic lymphadenectomy and gastrointestinal reconstruction and reflects the learning curve associated with minimally invasive surgery rather than a compromise in safety. In contrast, the reduction in intraoperative blood loss directly results from the magnified high-definition operative view, which facilitates precise dissection and meticulous hemostasis. This mechanism represents a key pathophysiological basis for the accelerated postoperative recovery associated with laparoscopic surgery [21]. Regarding postoperative recovery, the laparoscopic surgery group demonstrated significantly shorter times to abdominal drain removal, postoperative length of stay, and total hospitalization duration. These findings align closely with the theoretical framework of ERAS, and recovery was achieved with comparable oncological outcomes, consistent with a previous PSM study of locally advanced gastric cancer undergoing total gastrectomy [22].

Oncological radicality remains the most controversial issue concerning the application of laparoscopic surgery in patients with pT4a gastric cancer [23]. In the present study, no significant differences were observed between the two groups in the total number of harvested lymph nodes, the number of metastatic lymph nodes, or the distribution of postoperative N stages. These findings suggest that, within our cohort and when performed by experienced surgical teams, laparoscopic surgery can achieve a D2 lymphadenectomy extent comparable to that of open surgery, without compromising oncological radicality. This observation is consistent with the survival equivalence trend reported in the pT4a subgroup of the 5-year follow-up analysis of the CLASS-01 trial and with the lymph node retrieval findings of the KLASS-02 study [7,24]. It should be noted that the median number of harvested lymph nodes in our study (22–23 nodes) was slightly lower than that reported by some high-volume centers in East Asia. This discrepancy may be attributable to differences in baseline patient

characteristics, BMI distribution, and pathological specimen processing protocols. However, since these factors would affect both patient groups similarly, they do not compromise the validity of the comparative conclusions regarding the equivalence of lymphadenectomy extent between the two surgical approaches.

Lauren classification is a fundamental pathological classification system that reflects the biological behavior and growth patterns of gastric cancer, with distinct differences in invasion patterns, metastatic pathways, and prognosis among subtypes [11,12]. Testing for interaction between Lauren classification and surgical approach was a prespecified exploratory analysis rather than a primary study objective. Its outputs are hypothesis-generating for future precision-focused investigations and cannot support definitive clinical decision-making. No statistically significant interaction was observed between surgical approach and Lauren classification across outcomes related to surgical trauma, postoperative recovery, and oncological radicality. However, the absence of a statistically significant interaction should not be interpreted as evidence that Lauren classification has no true effect-modifying role. Interaction analyses generally require substantially larger sample sizes than main-effect analyses, often requiring more than four times the sample size to detect effects of comparable magnitude. The subgroup sample sizes in this study were limited, particularly in the intestinal-type subgroup, which included only 17 patients. Consequently, the current study was sufficiently powered only to detect very strong interaction effects and cannot exclude the possibility of weak-to-moderate effect modification.

Numerically, the direction of favorable effects of laparoscopy regarding trauma mitigation and accelerated recovery was consistent across all three Lauren subtypes. Point-estimate magnitudes appeared more pronounced in the intestinal-type subgroup and attenuated in the diffuse-type subgroup, yet none of these inter-subgroup differences reached statistical significance. Importantly, the absence of a statistically significant interaction does not equate to homogeneous treatment effects across subgroups. Constrained by sample size and statistical power, the present study could only detect strong effect modification and cannot rule out genuine weak-to-moderate subgroup disparities. This observed trend bears biological plausibility. Intestinal-type gastric cancer typically forms glandular architectures with relatively circumscribed expansive growth and well-defined tumor borders. By contrast, diffuse-type gastric cancer is characterized by infiltrative spread; tumor cells permeate the gastric wall diffusely and frequently elicit prominent desmoplastic responses that distort anatomical planes [11]. Accordingly, anatomical dissection and radical resection may be technically more demanding during laparoscopic surgery for diffuse-type tumors. Nevertheless, these subgroup observations remain exploratory. Limited sample size precludes definitive clinical recommendations, and these findings merely furnish hypotheses to be tested in larger cohorts. Whether Lauren classification can guide surgical selection for pT4a gastric cancer warrants well-designed prospective multicenter validation.

This study has several limitations. First, the retrospective single-center design is inherently susceptible to selection and information biases. Although propensity score matching effectively balanced measured baseline confounders, residual confounding from unmeasured factors, such as surgeon expertise, anesthesia management protocols, institution-specific discharge criteria, postoperative care pathways, and healthcare resource allocation practices, cannot be completely excluded. Because postoperative hospital stay may be influenced by variations in institutional clinical management and discharge processes, the generalizability of LOS-based outcomes across different healthcare settings should be interpreted with caution. Additionally, because the prediction model was developed using a propensity score–matched cohort, the distribution of surgical approaches and baseline characteristics may differ from that of the broader pT4a gastric cancer population. Therefore, further validation in independent external cohorts is required before its wider clinical application. Second, subgroup analyses by Lauren classification are exploratory and hampered by limited sample size and low power for interaction testing. They serve exclusively to generate research hypotheses rather than draw firm conclusions, and therefore, these analyses require further validation in large-scale multicenter studies. Third, this study focused primarily on short-term perioperative outcomes, and long-term oncological outcomes were unavailable. The long-term oncological outcomes in pT4a gastric cancer patients receiving laparoscopic surgery require further confirmation through prospective studies. Fourth, the prediction model is applicable only for postoperative risk stratification during hospitalization, as it incorporates postoperative pathological variables, and therefore cannot be used for preoperative surgical decision-making. Because the model had only been internally validated within a single institution, external validation in independent cohorts is required to confirm its generalizability. Fifth, only leukocyte differential percentages (relative values), rather than absolute leukocyte counts, were available in the original dataset. While NLR and LMR remain valid as total white blood cell count cancels out in their calculations, the conventional platelet-to-lymphocyte ratio could not be determined. We therefore reported the platelet-to-lymphocyte percentage ratio (PL%R), a related but distinct inflammatory index whose cut-offs cannot be directly applied to conventional PLR. Notably, PL%R has been validated in limited studies, and its prognostic role in pT4a gastric cancer warrants further validation in cohorts with absolute leukocyte counts to enable direct comparison with standard PLR.

In summary, we found that surgical approach, histological differentiation, N-stage, and intraoperative blood loss rep-

resent the independent predictors of prolonged postoperative hospital stay after total gastrectomy for pT4a gastric cancer. The derived risk prediction model demonstrated satisfactory discriminative performance, good calibration, and a net clinical benefit. In real-world clinical settings, it enables in-hospital risk stratification and delivers quantitative evidence to support individualized perioperative care, as soon as postoperative pathological reports are available. Secondary analyses indicated that laparoscopic D2 gastrectomy performed by an experienced surgical team at our center achieves comparable lymph-node dissection while providing the benefits of a minimally invasive approach and facilitating faster postoperative recovery, supporting its use as a safe surgical alternative for patients with pT4a gastric cancer. Exploratory analyses revealed broadly consistent outcome trends across Lauren subtypes. No statistically significant effect modification was identified, although true subgroup differences cannot be excluded owing to the limited sample size in this study. These observations require validation in large-cohort, multicenter studies. Nonetheless, the present findings offer practical insights for refining perioperative management of pT4a gastric cancer and inform future precision-oriented research.

Conclusions

Following propensity score matching, this study identified surgical approach, histological differentiation, N-stage, and intraoperative blood loss as independent predictors of prolonged postoperative hospital stay among patients with pT4a gastric adenocarcinoma. The constructed risk prediction model demonstrates moderate discriminative performance and favorable calibration. It facilitates risk stratification as soon as pathological reports become available, supporting tailored perioperative strategies including intensified interventions for high-risk patients and enhanced recovery pathways for low-risk individuals. Meticulous intraoperative hemostasis is highlighted as a key modifiable target for perioperative optimization. Secondary analyses confirm that laparoscopy-assisted D2 gastrectomy achieves lymph-node dissection outcomes comparable to those of open surgery, alongside advantages of a minimally invasive approach, including smaller incisions, reduced intraoperative blood loss, earlier abdominal drain removal and shorter hospitalization. These real-world perioperative outcomes corroborate the independent protective effect of laparoscopy identified in the prediction model. Mechanistically, laparoscopy reduces the risk of prolonged hospital stay by mitigating surgical trauma and accelerating postoperative recovery, reinforcing the clinical interpretability of this core model variable. No statistically significant interaction was detected between Lauren histotype and surgical modality. Directional treatment effects of laparoscopy were consistent across subtypes. Nonetheless, lack of statistical heterogeneity does not establish uniform treatment effects. The limited sample sizes within subgroups and low statistical power for interaction testing indicate that potential effect modification by Lauren classification cannot be excluded. These exploratory findings should be considered hypothesis-generating, and definitive subtype-specific conclusions will require validation in large-scale, multicenter studies.

Availability of Data and Materials

The data analyzed during the current study are available from the corresponding author upon reasonable request.

Author Contributions

BD: Data curation, Formal analysis, Writing – original draft. KL: Data acquisition, Resources, Literature collation. RYL: Data validation, Investigation, Result interpretation. ZJL: Methodology. SSC: Conceptualization, Project administration, Supervision. All authors contributed to the critical revision of the manuscript for important intellectual content. All authors have read and approved the final submitted version of the manuscript. All authors have made substantial intellectual contributions to the work, and agreed to be personally accountable for the accuracy and integrity of all parts of the research.

Ethics Approval and Consent to Participate

This retrospective cohort study was conducted with the approval of the Institutional Review Board of the General Hospital of Ningxia Medical University (Ethics Approval Number: KYLL-2026-1127). All procedures were performed in accordance with the ethical standards of the institutional research committee and the Declaration of Helsinki and its subsequent amendments. The requirement to obtain written informed consent was waived due to the retrospective nature of the chart review, absence of additional patient interventions, and full anonymization of all clinical and pathological identifiers to protect participant confidentiality.

Acknowledgment

Not applicable.

Funding

This research received no external funding.

Conflict of Interest

The authors declare no conflict of interest.

References

[1] Sung H, Ferlay J, Siegel RL, Laversanne M, Soerjomataram I, Jemal A, et al. Global Cancer Statistics 2020: GLOBOCAN Estimates of Incidence and Mortality Worldwide for 36 Cancers in 185 Countries. CA: a Cancer Journal for Clinicians. 2021; 71: 209–249. https://doi.org/10.3322/caac.21660

[2] Han B, Zheng R, Zeng H, Wang S, Sun K, Chen R, et al. Cancer inci-

dence and mortality in China, 2022. Journal of the National Cancer Center. 2024; 4: 47–53. https://doi.org/10.1016/j.jncc.2024.01.006

[3] Health Commission Of The People's Republic Of China N. National guidelines for diagnosis and treatment of gastric cancer 2022 in China (English version). Chinese Journal of Cancer Research = Chung-kuo Yen Cheng Yen Chiu. 2022; 34: 207–237. https://doi.org/10.21147/j.issn.1000-9604.2022.03.04

[4] Qiu J, Pankaj P, Jiang H, Zeng Y, Wu H. Laparoscopy versus open distal gastrectomy for advanced gastric cancer: a systematic review and meta-analysis. Surgical Laparoscopy, Endoscopy & Percutaneous Techniques. 2013; 23: 1–7. https://doi.org/10.1097/SLE.0b013e3182747af7

[5] Kim HH, Han SU, Kim MC, Kim W, Lee HJ, Ryu SW, et al. Effect of Laparoscopic Distal Gastrectomy vs Open Distal Gastrectomy on Long-term Survival Among Patients With Stage I Gastric Cancer: The KLASS-01 Randomized Clinical Trial. JAMA Oncology. 2019; 5: 506–513. https://doi.org/10.1001/jamaoncol.2018.6727

[6] Lou S, Yin X, Wang Y, Zhang Y, Xue Y. Laparoscopic versus open gastrectomy for gastric cancer: A systematic review and meta-analysis of randomized controlled trials. International Journal of Surgery (London, England). 2022; 102: 106678. https://doi.org/10.1016/j.ijsu.2022.106678

[7] Hu Y, Huang C, Sun Y, Su X, Cao H, Hu J, et al. Morbidity and Mortality of Laparoscopic Versus Open D2 Distal Gastrectomy for Advanced Gastric Cancer: A Randomized Controlled Trial. Journal of Clinical Oncology : Official Journal of the American Society of Clinical Oncology. 2016; 34: 1350–1357. https://doi.org/10.1200/JCO.2015.63.7215

[8] Hyung WJ, Yang HK, Park YK, Lee HJ, An JY, Kim W, et al. Long-Term Outcomes of Laparoscopic Distal Gastrectomy for Locally Advanced Gastric Cancer: The KLASS-02-RCT Randomized Clinical Trial. Journal of Clinical Oncology : Official Journal of the American Society of Clinical Oncology. 2020; 38: 3304–3313. https://doi.org/10.1200/JCO.20.01210

[9] Lordick F, Carneiro F, Cascinu S, Fleitas T, Haustermans K, Piessen G, et al. Gastric cancer: ESMO Clinical Practice Guideline for diagnosis, treatment and follow-up. Annals of Oncology : Official Journal of the European Society for Medical Oncology. 2022; 33: 1005–1020. https://doi.org/10.1016/j.annonc.2022.07.004

[10] Batista TP, Martins MR. Lymph node dissection for gastric cancer: a critical review. Oncology Reviews. 2012; 6: e12. https://doi.org/10.4081/oncol.2012.e12

[11] Lauren P. The two histological main types of gastric carcinoma: diffuse and so-called intestinal-type carcinoma: an attempt at a histo-clinical classification. Acta Pathologica Microbiologica Scandinavica. 1965; 64: 31–49. https://doi.org/10.1111/apm.1965.64.1.31

[12] Machlowska J, Baj J, Sitarz M, Maciejewski R, Sitarz R. Gastric Cancer: Epidemiology, Risk Factors, Classification, Genomic Characteristics and Treatment Strategies. International Journal of Molecular Sciences. 2020; 21: 4012. https://doi.org/10.3390/ijms21114012

[13] Yao Q, Sun QN, Wang DR. Laparoscopic versus open distal gastrectomy for advanced gastric cancer in elderly patients: a propensity-score matched analysis. World Journal of Surgical Oncology. 2024; 22: 13. https://doi.org/10.1186/s12957-023-03269-2

[14] Katai H, Mizusawa J, Katayama H, Takagi M, Yoshikawa T, Fukagawa T, et al. Short-term surgical outcomes from a phase III study of laparoscopy-assisted versus open distal gastrectomy with nodal dissection for clinical stage IA/IB gastric cancer: Japan Clinical Oncology Group Study JCOG0912. Gastric Cancer : Official Journal of the International Gastric Cancer Association and the Japanese Gastric Cancer Association. 2017; 20: 699–708. https://doi.org/10.1007/s10120-016-0646-9

[15] Al Gazzar HH, El-Badry AM, El-Bedewy TA, El-Naggar GF. Platelet to Lymphocyte Percentage Ratio As a Marker of Arterial Stiffness in Hemodialysis Patients. Journal of Advances in Medicine and Medical Research. 2021; 33: 102–112. https://doi.org/10.9734/jammr/2021/v33i1130930

[16] Mrdutt MM, Isbell CL, Thomas JS, Shaver CN, Essani R, Warrier R, et al. Impact of complications on length of stay in elective laparoscopic colectomies. The Journal of Surgical Research. 2017; 219: 180–187. https://doi.org/10.1016/j.jss.2017.05.113

[17] Healy GL, Stuart CM, Dyas AR, Bronsert MR, Meguid RA, Anioke T, et al. Association between postoperative complications and hospital length of stay: a large-scale observational study of 4,495,582 patients in the American College of Surgeons National Surgical Quality Improvement Program (ACS-NSQIP) registry. Patient Safety in Surgery. 2024; 18: 29. https://doi.org/10.1186/s13037-024-00409-9

[18] Shaw-Stiffel TA, Zarny LA, Pleban WE, Rosman DD, Rudolph RA, Bernstein LH. Effect of nutrition status and other factors on length of hospital stay after major gastrointestinal surgery. Nutrition (Burbank, Los Angeles County, Calif.). 1993; 9: 140–145.

[19] Ma Z, Bao X, Gu J. Effects of laparoscopic radical gastrectomy and the influence on immune function and inflammatory factors. Experimental and Therapeutic Medicine. 2016; 12: 983–986. https://doi.org/10.3892/etm.2016.3404

[20] Alves Bersot CD, Ferreira Gomes Pereira L, Goncho VGV, Pereira JEG, Falcão LFDR. Enhancing recovery and reducing inflammation: the impact of enhanced recovery after surgery recommendations on inflammatory markers in laparoscopic surgery-a scoping review. Frontiers in Surgery. 2024; 11: 1450434. https://doi.org/10.3389/fsurg.2024.1450434

[21] Park YK, Yoon HM, Kim YW, Park JY, Ryu KW, Lee YJ, et al. Laparoscopy-assisted versus Open D2 Distal Gastrectomy for Advanced Gastric Cancer: Results From a Randomized Phase II Multicenter Clinical Trial (COACT 1001). Annals of Surgery. 2018; 267: 638–645. https://doi.org/10.1097/SLA.0000000000002168

[22] Hu HT, Ma FH, Xiong JP, Li Y, Jin P, Liu H, et al. Laparoscopic *vs* open total gastrectomy for advanced gastric cancer following neoadjuvant therapy: A propensity score matching analysis. World Journal of Gastrointestinal Surgery. 2022; 14: 161–173. https://doi.org/10.4240/wjgs.v14.i2.161

[23] Tran DQ, Vo Duy L, Nguyen VH, Dang QT, Nguyen DT, Nguyen AV, et al. Laparoscopic versus open distal gastrectomy for clinical T4a gastric cancer: Short-term outcomes and interim survival analysis of the UMC-UPPERGI-01 randomized clinical trial. Journal of Clinical Oncology. 2026; 44: e16142. https://doi.org/10.1200/JCO.2026.44.16_suppl.e16142

[24] Lee HJ, Hyung WJ, Yang HK, Han SU, Park YK, An JY, et al. Short-term Outcomes of a Multicenter Randomized Controlled Trial Comparing Laparoscopic Distal Gastrectomy With D2 Lymphadenectomy to Open Distal Gastrectomy for Locally Advanced Gastric Cancer (KLASS-02-RCT). Annals of Surgery. 2019; 270: 983–991. https://doi.org/10.1097/SLA.0000000000003217