Original Article

Postoperative outcomes, lymph node metastasis patterns, prognostic factors, and ai-assisted postoperative station-level nodal risk prediction in ESCC patients undergoing minimally invasive McKeown esophagectomy

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Abstract

Background: The extent and targets of lymphadenectomy for esophageal squamous cell carcinoma (ESCC) remain debated, and clinically intuitive visualizations of station-specific metastasis may facilitate surgical decision-making. ABO blood group has been proposed as a host-related biomarker in several malignancies, but its role in nodal spread and survival in ESCC is unclear.

Methods: We retrospectively analyzed a consecutive cohort of 909 ESCC patients treated with curative McKeown minimally invasive esophagectomy between Jan 2012 and Jan 2019. Metastatic patterns were visualized using heatmaps based on node-based metastatic rates and patient-based positivity. Logistic regression, Kaplan-Meier analysis, and Cox proportional hazards regression were performed to evaluate associations between ABO blood type, lymph node metastasis, maximum tumor diameter, and overall survival (OS). In an exploratory AI-assisted prediction analysis, postoperative multivariable logistic regression models were developed for individualized station-level nodal metastasis prediction using age, sex, tumor location, ABO blood type, tumor differentiation, pT stage, and pN stage, and evaluated by 5-fold cross-validation.

Results: The cohort had a mean age of 64.1 ± 7.5 years, with 58.9% males. The most common tumor location was the middle esophagus (n = 603), and most patients had pT3 disease (44.8%) and pN0 status (61.8%). Postoperative complications included pulmonary complications (9.8%), recurrent laryngeal nerve injury (8.8%), and anastomotic leak (8.1%). Lymph node metastasis mapping revealed heterogeneous dissemination patterns with distinct “hotspots” across cervical and mediastinal stations. ABO blood type was not significantly associated with nodal metastasis (O *vs.* non-O: OR = 1.01, P = 0.947; B *vs.* non-B: OR = 1.29, P = 0.104). However, Kaplan-Meier analysis showed significantly worse OS in the O blood group compared to non-O

groups (median survival: 50 *vs.* 87 months, $P = 0.013$), while B *vs.* non-B groups showed no significant difference ($P = 0.778$). Lymph node metastasis and longer maximum tumor diameter (> 3.79 cm) were independently associated with reduced OS (all $P < 0.0001$). The AI-assisted postoperative station-level prediction models showed good discrimination across key nodal basins, with the highest AUROC values observed for stations 2R, 17, and 8 (0.889, 0.881, and 0.879, respectively).

Conclusions: In ESCC patients undergoing minimally invasive McKeown esophagectomy, ABO blood type was not associated with nodal metastasis. ABO-related differences in overall survival were observed, but after multivariable adjustment only blood group AB was associated with a lower hazard of death versus blood group A, whereas blood groups B and O were not statistically significant. Station-specific metastasis mapping may inform risk-adapted lymphadenectomy strategies, and postoperative station-level prediction models may complement descriptive nodal mapping by providing individualized nodal risk estimates.

Keywords: Esophageal squamous cell carcinoma, minimally invasive McKeown esophagectomy, lymph node metastasis, artificial intelligence, AI-assisted prediction, station-level risk prediction, model validation, calibration

INTRODUCTION

Esophageal squamous cell carcinoma (ESCC) remains a major global health challenge, characterized by high morbidity and mortality[1]. It is the predominant histological subtype of esophageal cancer in Asia, accounting for approximately 90% of cases[2]. Despite advances in multimodal therapy, surgical resection, particularly esophagectomy, continues to be the cornerstone of curative treatment for localized and locoregionally advanced disease[3]. Over the past two decades, the surgical paradigm has shifted from open esophagectomy to minimally invasive approaches, driven by evidence from randomized trials demonstrating reduced pulmonary complications and comparable oncological outcomes[4,5]. The minimally invasive McKeown esophagectomy has gained

widespread adoption due to its potential benefits of reduced surgical trauma, fewer postoperative complications, and faster recovery compared to open approaches[6]. However, the optimal extent of lymphadenectomy during MIE remains debated, and postoperative complication rates, particularly recurrent laryngeal nerve injury and anastomotic leak, continue to be areas of active investigation[7,8]. Moreover, long-term survival for ESCC patients remains unsatisfactory, largely due to a high propensity for early lymph node metastasis and subsequent disease recurrence.

Accurate prognostic stratification is crucial for guiding adjuvant therapy and follow-up strategies[9]. While established clinicopathological factors such as pathological T and N stage, maximum tumor diameter, and differentiation grade are routinely used[10], and have been validated in large multicenter cohorts[11,12], there is growing interest in identifying novel, readily available biological markers that can refine risk assessment. The ABO blood group system, determined by inherited carbohydrate antigens expressed on erythrocytes and various epithelial cells[13], has been implicated in cancer pathogenesis, progression, and prognosis for several malignancies, including gastric and pancreatic cancers[14-17]. The biological rationale may involve alterations in cell adhesion, membrane signaling, and immune modulation associated with different blood group antigens[18-21]. However, its prognostic role in ESCC, especially in the context of modern minimally invasive surgery, remains ambiguous and warrants further investigation. To date, only a few retrospective studies have examined the association between ABO blood type and ESCC prognosis, with conflicting results, and none has focused on patients undergoing uniform MIE procedures[22,23].

Furthermore, a detailed understanding of the lymphatic drainage pattern of ESCC is essential for performing an oncologically adequate lymphadenectomy. While the prevalence of lymph node metastasis is a known critical prognostic factor[24], the anatomical distribution or “map” of nodal involvement, particularly its variation with primary tumor location, is complex and can inform surgical planning[25]. A station-specific analysis using both node-based and patient-based metrics can provide a

more nuanced view of metastatic patterns, identifying high-risk "hotspot" stations that may require particular attention during dissection. Such detailed mapping is particularly relevant for optimizing the extent of lymphadenectomy in MIE, where complete dissection of certain stations (e.g., left recurrent laryngeal nerve chain) can be technically challenging but oncologically necessary[26].

However, conventional nodal mapping remains primarily descriptive at the cohort level and does not directly provide individualized estimates of station-specific metastatic risk. In recent years, prediction modeling approaches have increasingly been explored for nodal metastasis assessment and cancer risk stratification, offering the potential for more personalized postoperative risk evaluation[27,28]. Therefore, in an exploratory analysis, we additionally applied multivariable logistic regression models to develop postoperative station-level nodal risk prediction models and to generate individualized nodal risk profiles.

This study aimed to investigate three interconnected aspects in a large, homogeneous cohort of ESCC patients undergoing minimally invasive McKeown esophagectomy: first, to analyze station-specific lymph node metastatic patterns stratified by tumor location; second, to evaluate the prognostic significance of the ABO blood group system alongside traditional clinicopathological factors such as maximum tumor diameter and nodal metastasis status on overall survival; and third, to develop and internally validate AI-assisted postoperative station-level models for individualized nodal risk prediction.

METHODS

Study design and ethics

This retrospective cohort analysis was conducted in accordance with institutional policies and ethical standards. The cohort was derived from a phase III clinical trial framework (ClinicalTrials.gov identifier: NCT02448979) with ethics approval noted in institutional records.

Patients

Consecutive patients with pathologically confirmed ESCC undergoing curative McKeown MIE between Jan 2012 and Jan 2019 were included. Inclusion criteria encompassed resectable disease without distant metastasis and fitness for surgery (ASA I-III). Exclusion criteria included neoadjuvant therapy and incomplete medical records. Preoperative evaluation included endoscopy, CT imaging, cardiopulmonary assessment, and routine staging workup.

Data collection and definitions

Baseline demographic, clinical, and surgical data were extracted. Preoperative ABO blood type was determined from standard serological tests recorded in the anesthesia or transfusion medicine records. Pathological data were obtained from final postoperative histopathology reports, including tumor location (upper, middle, or lower third of the esophagus, according to the AJCC 8th edition guidelines), pT and pN stage, tumor differentiation grade (well, moderate, or poor), and maximum tumor diameter (cm). A systematic two-field (thoraco-abdominal) or three-field (thoraco-abdomino-cervical) lymphadenectomy was performed according to institutional protocol. All resected lymph nodes were meticulously examined by experienced pathologists. Lymph node stations were defined and numbered according to the Japanese Classification of Esophageal Cancer (11th edition) and the AJCC system. For the mapping analysis, stations were grouped as: cervical (right/left), upper mediastinal (2R, 2L, 3P, 4R, 4L), mid-lower mediastinal (7, 8, 9), and abdominal (10, 15, 16, 17).

Definitions of nodal outcomes and mapping metrics

Node-based metastatic rate: For each lymph node station, calculated as: (Total number of metastatic nodes in that station across all patients) / (Total number of dissected nodes in that station across all patients) × 100%.

Patient-based nodal positivity: For each station, defined as the percentage of patients who had at least one metastatic lymph node in that specific station.

For both node-based metastatic rates and patient-based positivity estimates, exact numerator/denominator values were recorded and 95% confidence intervals were calculated for each station-location stratum.

AnyLN_pos: A patient-level variable indicating the presence of lymph node metastasis in any dissected station (pN+).

Statistical analysis

Continuous variables were summarized as mean ± SD or median (IQR), and categorical variables as counts (%). Station-specific metastatic maps were visualized by tumor location strata. For AnyLN_pos, multivariable logistic regression adjusted for age, sex, tumor location, differentiation grade, and pathological T stage. Overall survival was assessed by Kaplan-Meier curves and compared using log-rank tests. Hazard ratios (HRs) with 95% confidence intervals (CIs) for survival outcomes were estimated using Cox proportional hazards regression. Two-sided $P < 0.05$ was considered statistically significant.

AI-assisted postoperative station-level nodal risk prediction

In this exploratory analysis, we developed postoperative multivariable logistic regression models to estimate individualized station-level nodal metastasis risk. Model performance was evaluated using 5-fold cross-validation, with discrimination assessed by the area under the receiver operating characteristic curve (AUROC). Calibration was assessed for the seven main nodal stations (2R, 17, 8, 2L, 16, 7, and 3-4) using out-of-fold predicted probabilities from 5-fold cross-validation by comparing mean predicted probabilities with observed metastasis rates across quantile-based risk bins. Decision curve analysis based on out-of-fold predictions was additionally performed for station 17.

RESULTS

Patient characteristics

A total of 909 patients with ESCC who underwent minimally invasive McKeown esophagectomy were included, and their baseline demographic and clinicopathological characteristics are summarized in Table 1. Overall, the mean age was 64.1 ± 7.5 years, 58.9% of patients were male, tumors were most commonly located in the middle esophagus (*n* = 603), and the cohort was dominated by pT3 disease (44.8%) and pN0 status (61.8%).

Table 1. Demographics and clinicopathological parameters.

Variables	N = 909	Rate(%)
Demographics	Age (mean ± SD)	64.1 ± 7.5
	Male: *n* (%)	535(58.9)
	Female: *n* (%)	374(41.1)
ASA class	ASA-1: *n* (%)	637(70.1)
	ASA-2: *n* (%)	245(27.0)
	ASA-3: *n* (%)	27(2.9)
Comorbidity	Hypertension: *n* (%)	193(21.2)
	Diabetes: *n* (%)	60(6.6)
	COPD: *n* (%)	12(1.3)
	Liver cirrhosis: *n* (%)	6(0.7)
	Coronary artery disease: *n* (%)	24(2.6)
Location of lesion	Upper third: *n* (%)	200(22.0)
	Middle third: *n* (%)	603(66.3)
	Lower third: *n* (%)	106(11.7)
Maximum tumor diameter	≤ 3 cm: *n* (%)	358(39.4)
	3-5 cm: *n* (%)	323(35.5)
	≥ 5 cm: *n* (%)	228(25.1)
Pathological T stage (%)	Tis-1: *n* (%)	216(23.8)
	T2: *n* (%)	203(22.3)

	T3: *n* (%)	407(44.8)
	T4: *n* (%)	83(9.1)
Pathological N stage (%)	N0: *n* (%)	562(61.8)
	N1: *n* (%)	223(24.5)
	N2: *n* (%)	96(10.6)
	N3: *n* (%)	28(3.1)
Pathological TNM stage (%)	Stage 0-IB: *n* (%)	198(21.8)
	IIA: *n* (%)	143(15.8)
	IIB: *n* (%)	202(22.3)
	IIIA: *n* (%)	57(6.3)
	IIIB: *n* (%)	247(27.2)
	IVA: *n* (%)	60(6.6)

Postoperative complications

Postoperative complications among 909 patients undergoing minimally invasive McKeown esophagectomy are summarized in Supplementary Figure 1. The most frequent complications were pulmonary complications (9.8%), recurrent laryngeal nerve injury (8.8%), and anastomotic leak (8.1%), followed by cardiovascular complications (5.0%), gastrointestinal complications (3.6%), thoracic complications (3.4%), and incisional complications (3.0%), whereas chylothorax (2.4%), bleeding (1.7%), and other complications (1.3%) were less common.

Station-specific metastatic mapping

Station-specific nodal metastasis was summarized using node-based metastatic rate and patient-based positivity, stratified by tumor location (upper/middle/lower). The maps demonstrated heterogeneous dissemination patterns across stations and tumor locations, with visually apparent “hotspots” in selected stations [Figure 1]. Exact numerator/denominator data and corresponding 95% confidence intervals for the node-based metastatic rates and patient-based positivity estimates are provided in Supplementary Tables 2 and 3, respectively.

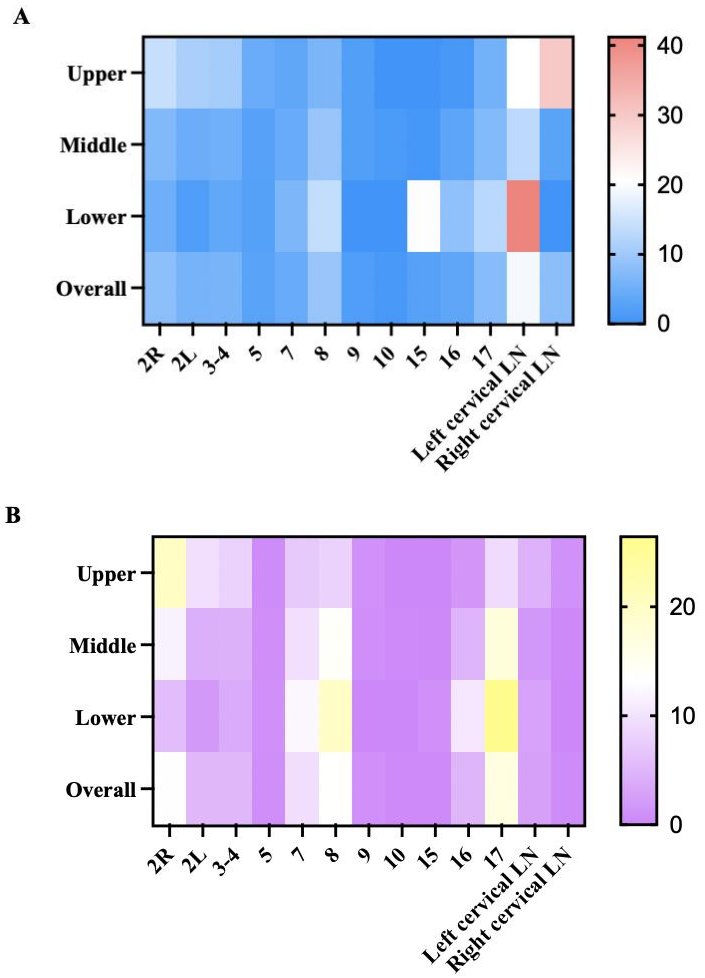


Figure 1. Station-specific lymph node metastasis maps stratified by tumor location. (A) Heatmap of node-based metastatic rate across nodal stations according to primary tumor location (upper, middle, lower esophagus, and total cohort). Each cell represents the percentage of metastatic nodes among all dissected nodes at the corresponding station; (B) Heatmap of patient-based nodal positivity across nodal stations according to primary tumor location. Each cell represents the percentage of patients with at least one metastatic node at the corresponding station. Together, these maps provide complementary overviews of station-specific metastatic burden and patient-level positivity, highlighting nodal "hotspots" across tumor locations. Exact numerator/denominator data and corresponding 95% confidence intervals for these heatmap estimates are provided in Supplementary Tables 2 and 3.

AI-assisted postoperative station-level nodal risk prediction

Table 2. Performance of AI-assisted postoperative station-level nodal metastasis prediction using the enhanced model.

Nodal station	N	AUROC (5-fold CV)
2R	837	0.889 ± 0.020
17	887	0.881 ± 0.039
8	796	0.879 ± 0.053
2L	529	0.845 ± 0.048
16	729	0.818 ± 0.114
7	882	0.807 ± 0.049
3-4	449	0.788 ± 0.066

Values are mean ± SD AUROC from 5-fold cross-validation. Models were trained among cases with the corresponding station assessed (obs = 1). Predictors included pT and pN together with age, sex, tumor location, ABO blood type, and tumor differentiation.

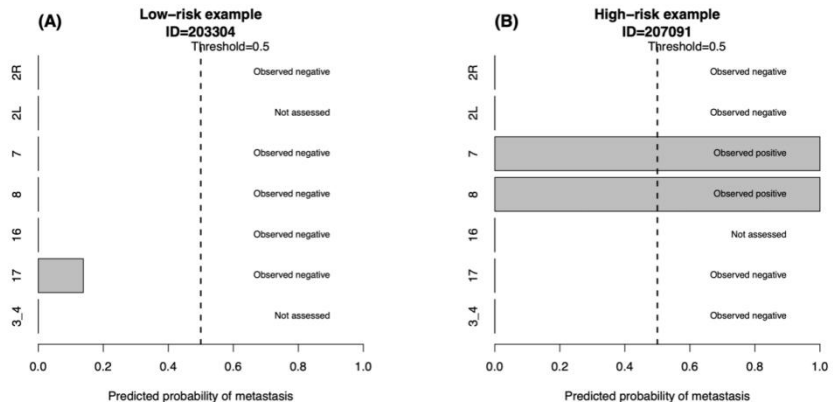


Figure 2. Individualized station-level nodal risk profiles for two representative patients. (A) Low-risk example (ID 203304); (B) High-risk example (ID 207091). Bars represent predicted probabilities of nodal metastasis across stations derived from the postoperative enhanced model (pT + pN plus age, sex, tumor location, ABO blood type, and differentiation). The dashed vertical line indicates the illustrative high-risk threshold (probability = 0.5). Observed nodal status is annotated for assessed stations (obs = 1); “Not assessed” indicates stations without evaluation.

Using the postoperative enhanced model incorporating pT and pN together with age, sex, tumor location, ABO blood type, and tumor differentiation, the AI-assisted station-level prediction analysis achieved high discrimination across key nodal basins [Table 2]. The highest 5-fold cross-validated AUROC was observed for station 2R (0.889 ± 0.020; n = 837), followed by station 17 (0.881 ± 0.039; n = 887) and station 8 (0.879 ± 0.053; n = 796). Performance remained robust for station 2L (0.845 ± 0.048; n = 529), station 16 (0.818 ± 0.114; n = 729), station 7 (0.807 ± 0.049; n = 882), and stations 3-4 (0.788 ± 0.066; n = 449).

To illustrate individualized risk profiling, Figure 2 shows representative low-risk and high-risk cases, demonstrating substantial heterogeneity in predicted probabilities across nodal stations. At the cohort level, the distribution of predicted probabilities for each station is summarized in Supplementary Figure 2. Calibration plots for the seven main nodal stations (2R, 17, 8, 2L, 16, 7, and 3-4) are shown in Supplementary Figure 3, demonstrating the agreement between out-of-fold predicted probabilities and observed event rates across risk deciles, with overall acceptable calibration across stations. For station 17, incremental model enhancement showed minimal gain from adding tumor differentiation to the pre/perioperative baseline, whereas adding pT substantially improved discrimination and adding pN yielded the largest performance gain [Supplementary Table 1]. Decision curve analysis for station 17 is shown in Supplementary Figure 4.

ABO blood type and any nodal metastasis (AnyLN_pos)

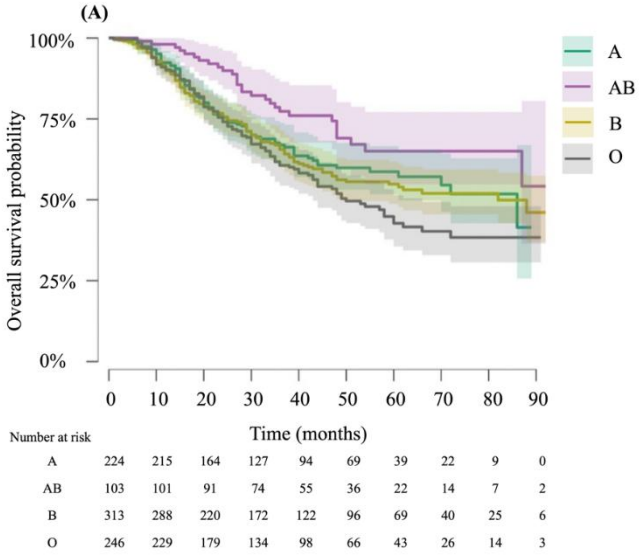
In unadjusted contingency analyses among patients with available blood type data (N = 903), neither O *vs.* non-O ($\chi^2 = 0.108$, $P = 0.742$) nor B *vs.* non-B ($\chi^2 = 2.501$, $P = 0.114$) was associated with AnyLN_pos.

In multivariable logistic regression adjusting for age, sex, tumor location, differentiation grade, and pathological T stage, O *vs.* non-O was not associated with AnyLN_pos (OR

= 1.01, 95% CI 0.732-1.396; P = 0.947). Similarly, B *vs.* non-B did not reach statistical significance (OR = 1.29, 95% CI 0.949-1.750; P = 0.104). As expected, increasing pathological T stage was strongly associated with AnyLN_pos.

Overall survival by blood type (Kaplan-Meier)

Kaplan-Meier analysis of the four ABO blood groups showed a significant overall difference in survival (overall log-rank χ^2 = 11.57, df = 3, P = 0.009; Figure 3A). Pairwise dichotomized comparisons showed no significant difference between B and non-B groups (log-rank χ^2 = 0.080, P = 0.778; Figure 3C), whereas O versus non-O demonstrated significant survival separation (log-rank χ^2 = 6.124, P = 0.013; Figure 3B), with median survival of 50 months in the O group versus 87 months in the non-O group.



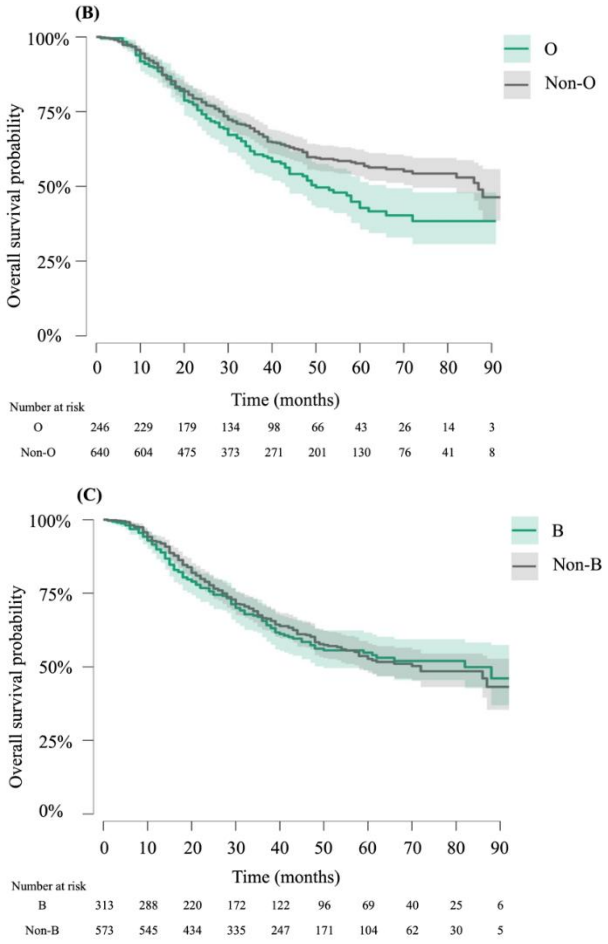


Figure 3. Kaplan-Meier curves for overall survival (OS) stratified by ABO blood group. (A) OS curves stratified by the four ABO blood groups (A, B, AB, and O); (B) OS curves comparing O versus non-O; (C) OS curves comparing B versus non-B.

Between-group differences were assessed using the log-rank test, and censored observations are indicated by tick marks. Two-sided *P* values are reported, with $P < 0.05$ considered statistically significant. The computed log-rank *P* values were 0.009 for the overall four-group comparison, 0.013 for O versus non-O, and 0.778 for B versus non-B.

To further determine whether ABO blood group remained associated with overall survival after adjustment for other clinicopathological variables, we performed multivariable Cox proportional hazards regression analysis.

Multivariable cox proportional hazards regression for overall survival

In multivariable Cox proportional hazards regression including ABO blood type, sex, tumor differentiation, pathological T stage, pathological N stage, and age, the overall model was significant (likelihood ratio $\chi^2 = 245.2$, df = 16, $P < 0.001$; Wald $\chi^2 = 214.8$, df = 16, $P < 0.001$). Compared with blood group A, blood group AB was associated with a significantly lower hazard of death (HR = 0.632, 95% CI 0.407-0.981), whereas blood group B (HR = 1.234, 95% CI 0.924-1.648) and blood group O (HR = 1.297, 95% CI 0.966-1.740) were not statistically significant. As expected, more advanced pathological T and N stages were independently associated with worse survival. The proportional hazards assumption was not violated for the overall model (global test: $\chi^2 = 17.426$, df = 16, $P = 0.359$).

After adjustment for sex, age, tumor differentiation, pT stage, and pN stage, blood group AB remained associated with a lower hazard of death compared with the reference group, whereas blood groups B and O did not reach statistical significance in the multivariable model. We next evaluated the prognostic impact of lymph node metastasis status and maximum tumor diameter on survival. Detailed hazard ratios for ABO blood groups and other covariates in the multivariable Cox model are provided in Supplementary Table 4.

Lymph node metastasis status and five-year survival

A total of 909 patients with ESCC were categorized according to lymph node metastasis status. Lymph node metastasis was identified in 347 patients, whereas 562 patients had no nodal metastasis [Figure 4A]. In Cox proportional hazards regression administratively censored at 60 months, lymph node metastasis was an adverse prognostic factor for five-year survival (HR = 2.092, 95% CI 1.625-2.254, $P < 0.0001$; Figure 4B).

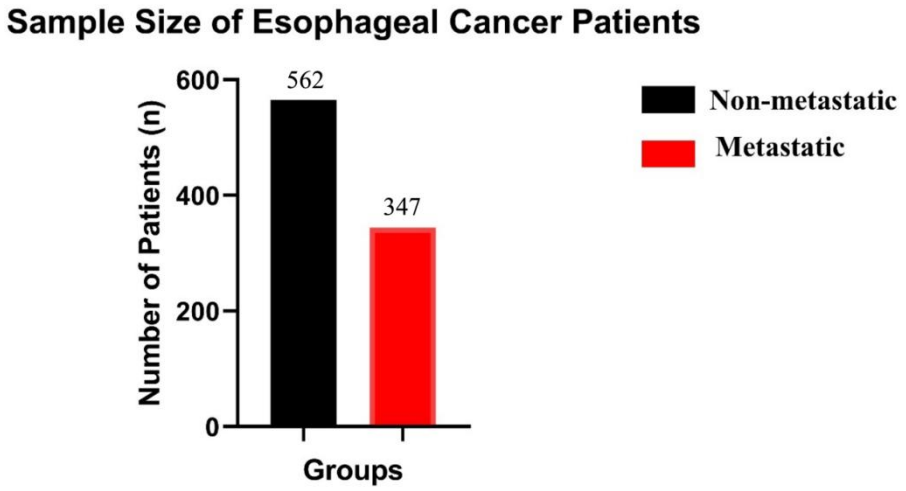


Figure 4. Lymph node metastasis status and five-year survival in ESCC. (A) Distribution of ESCC patients according to lymph node metastasis status (347 with nodal metastasis [pN+] and 562 without nodal metastasis [pN0]); (B) Cox proportional hazards regression (administratively censored at 60 months) showing the hazard ratio (HR) with 95% confidence interval (CI) for lymph node metastasis as a prognostic factor for five-year survival.

Cox regression for five-year survival (censored at 60 months)

	five-year survival	
	HR(95% CI)	*p*
pN+ *vs.* pN0	2.092(1.625-2.254)	$P < 0.0001$

Overall survival by maximum tumor diameter (Kaplan-Meier)

A cohort of 909 patients with esophageal squamous cell carcinoma (ESCC) was categorized based on the maximum tumor diameter. As presented in Figure 5A, the mean maximum diameter across all tumors was 3.79 cm. Patients were then stratified into two groups according to whether their tumor exceeded this mean value. Of these, 467 patients (51.4%) had a shorter tumor diameter (≤ 3.79 cm), while 442 patients (48.6%) had a longer tumor diameter (> 3.79 cm). Kaplan-Meier survival analysis revealed that patients with longer tumor diameter experienced significantly worse overall survival (OS; $P < 0.0001$; Figure 5B). Furthermore, Cox proportional hazards

regression identified maximum tumor diameter as an independent prognostic factor for OS, with a hazard ratio (HR) of 1.622 (95% confidence interval [CI]: 1.393-1.887; $P < 0.0001$; Figure 5C).

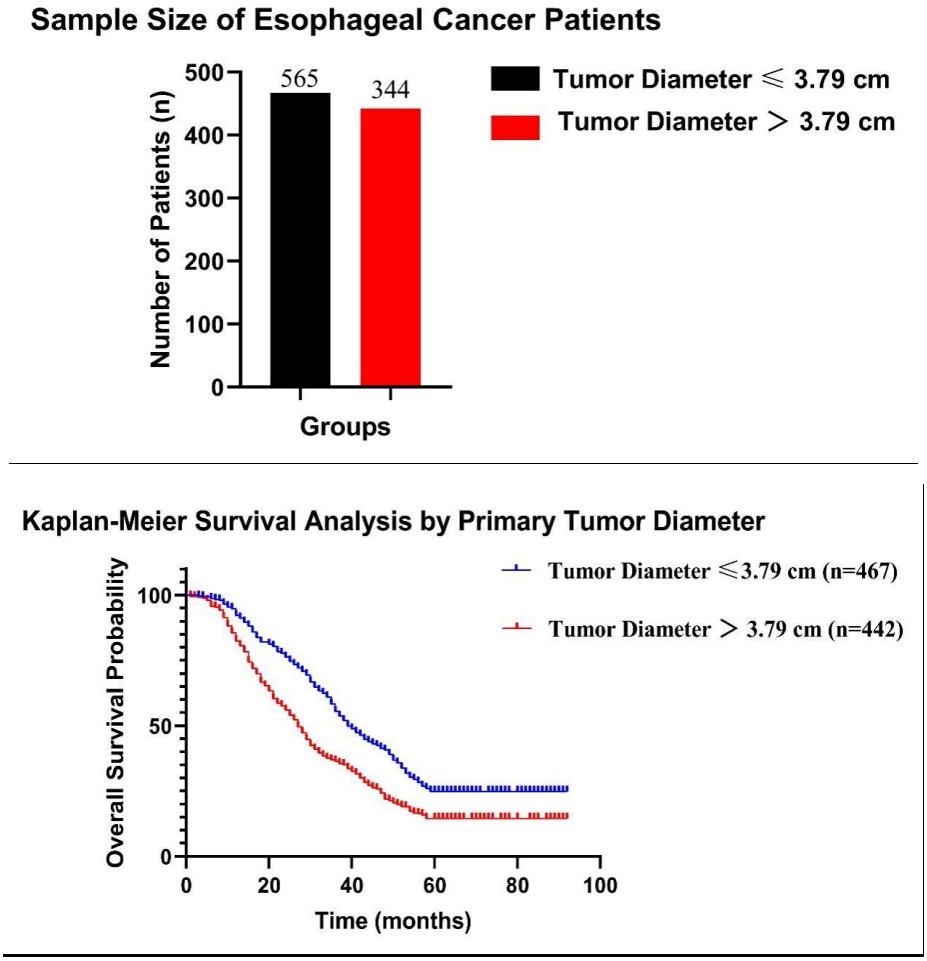


Figure 5. Patient distribution and prognostic impact of maximum tumor diameter in esophageal squamous cell carcinoma (ESCC). (A) Distribution of ESCC patients stratified by the mean maximum tumor diameter (3.79 cm); (B) Kaplan-Meier curve for overall survival (OS) stratified by maximum tumor diameter (long > 3.79 cm *vs.* short ≤ 3.79 cm). Between-group difference was assessed using the log- rank test, and censored observations are indicated by tick marks; (C) Forest plot from Cox proportional hazards regression showing the hazard ratio (HR) with 95% confidence interval (CI) for maximum tumor diameter as a prognostic factor for OS. Between-group differences were evaluated using the log- rank test. Two-sided *P* values are reported, with $P < 0.05$ considered statistically significant. (Computed log- rank *P* value for OS: < 0.0001;

HR = 1.622, 95% CI = 1.393-1.887, $P < 0.0001$.)

Cox proportional hazards regression for overall survival

maximum tumor diameter	overall survival	
	HR(95% CI)	*p*
Longer tumor diameter (> 3.79 cm) *vs.* shorter tumor diameter (≤ 3.79 cm)	1.622 (1.393-1.887)	$P < 0.0001$

DISCUSSION

In this large retrospective cohort of patients with ESCC undergoing minimally invasive McKeown esophagectomy, we identified clear station-specific patterns of lymphatic metastasis according to primary tumor location. Although ABO blood type was not associated with lymph node metastasis, survival differences were observed in unadjusted analyses, whereas multivariable Cox analysis supported only a lower hazard of death for blood group AB versus blood group A. Conventional tumor-burden indicators, particularly maximum tumor diameter and nodal metastasis, remained strong prognostic factors. In addition, the exploratory AI-assisted postoperative station-level prediction model showed good discrimination across several key nodal basins and enabled individualized nodal risk estimation.

The observed station-specific lymphatic metastasis patterns align with and refine the classical understanding of esophageal lymphatic drainage. Our heatmap analysis, utilizing both node-based metastatic rates and patient-based positivity, demonstrated that cervical and upper mediastinal stations (e.g., cervical, 2R, 4L) were frequent “hotspots” for upper and middle esophageal tumors, whereas lower esophageal tumors exhibited a higher propensity for abdominal stations (e.g., 16, 17). These findings reinforce the necessity of a meticulous and anatomically tailored lymphadenectomy and provide a visual, data-driven rationale for the extent of nodal dissection. The combined

use of node-based and patient-based metrics minimizes potential bias introduced by variability in the extent of lymph node harvest, offering a more clinically applicable representation of metastatic risk that can directly inform surgical planning. Our findings are consistent with previous reports on the pattern of lymphatic spread in ESCC, which have consistently emphasized the importance of upper mediastinal stations for middle and upper thoracic tumors[29,30]. However, the present study provides a more granular, station-level quantification in a large MIE cohort, which has been lacking in prior literature[31]. Furthermore, the identification of station 17 as a frequent abdominal hotspot for lower esophageal tumors supports the rationale for routine dissection of perigastric and celiac stations during McKeown esophagectomy[32].

Beyond descriptive nodal mapping at the cohort level, our exploratory postoperative prediction analysis extended these findings to individualized postoperative risk estimation at the station level. The model showed favorable discrimination across several key nodal basins and may complement conventional metastatic mapping by supporting postoperative nodal risk stratification, although external validation is still required before broader clinical application. Machine learning and logistic regression-based models for lymph node metastasis prediction have been increasingly explored in gastrointestinal cancers, including ESCC[33,34]. Our approach differs from previous efforts in that we focused on station-specific rather than overall nodal status, and we intentionally used only postoperative variables (including pT and pN stage) to generate individualized risk profiles. This design choice reflects a pragmatic clinical scenario: after surgery and pathological examination, clinicians could use such models to identify stations with high residual risk for consideration of adjuvant radiotherapy or more intensive surveillance.

An additional finding of our study is that ABO blood type showed prognostic relevance for overall survival, but the pattern should be interpreted cautiously. In unadjusted Kaplan-Meier analysis, overall survival differed across the four ABO groups, and O versus non-O also showed significant separation. However, in the multivariable Cox

model, only blood group AB was associated with a lower hazard of death compared with blood group A, whereas blood groups B and O were not statistically significant [Supplementary Table 4]. These findings suggest that any survival association of ABO blood type in ESCC may be modest and sensitive to adjustment for established clinicopathological factors. Given the inconsistent literature[22] and the retrospective nature of this study, further validation in independent cohorts is warranted.

Our results robustly reaffirm the prognostic centrality of conventional tumor-burden parameters. Greater maximum tumor diameter (> 3.79 cm) and the presence of lymph node metastasis were both independently associated with significantly reduced overall survival. These variables are readily accessible from routine pathological examination and should remain cornerstone elements in postoperative risk stratification and in +guiding decisions regarding adjuvant therapy. The postoperative complication profile observed in our cohort—predominantly pulmonary complications, recurrent laryngeal nerve injury, and anastomotic leak—is consistent with the recognized morbidity spectrum of McKeown esophagectomy and underscores the importance of surgical expertise and meticulous perioperative care in optimizing patient outcomes.

Several limitations of this study should be acknowledged. First, its retrospective, single-center design may introduce selection bias and limit the generalizability of the findings. Second, although we adjusted for key clinicopathological variables in our multivariate models, unmeasured confounders such as specific genetic alterations, detailed comorbidity profiles, or adherence to adjuvant therapy could influence survival outcomes. Third, the biological mechanisms underlying the observed survival disparity according to ABO blood group remain speculative and were not explored in this clinicopathological study. Fourth, the station-level prediction analysis was based on postoperative pathological variables and was internally validated using 5-fold cross-validation; therefore, external validation in independent multicenter cohorts is required before clinical implementation. Future prospective, multi-institutional investigations incorporating molecular profiling are warranted to validate our findings

and to elucidate the functional links between ABO antigens and ESCC aggressiveness.

CONCLUSION

In conclusion, this study provides a comprehensive analysis of outcomes following minimally invasive McKeown esophagectomy for ESCC. We present a refined, station-specific lymph node metastasis map that can inform the extent of surgical lymphadenectomy. In addition, exploratory AI-assisted postoperative station-level prediction models provided individualized nodal risk estimates and may complement conventional nodal mapping in postoperative risk stratification. Furthermore, ABO blood type was not associated with lymph node metastasis, and its association with overall survival should be interpreted cautiously; in the multivariable Cox model, blood group AB was associated with a lower hazard of death compared with blood group A, whereas blood groups B and O were not statistically significant.

DECLARATIONS

Authors' contributions

Contributed to the study design, data analysis, interpretation of the results, and manuscript drafting: H.L, W.Z, A.Z and J.L;

Contributed to data collection and manuscript revision: H.L, Z.H, S.N, X.W and X.Z;

Contributed to manuscript revision. All authors read and approved the final manuscript: L.Z.

Availability of data and materials

The original contributions presented in this study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

AI and AI-assisted tools statement

During the preparation of this work, the authors used ChatGPT for limited assistance with R/JASP command troubleshooting and language refinement. All statistical

analyses were designed, performed, and verified by the authors using JASP and R. All interpretations of the results and the final conclusions were made by the authors, who take full responsibility for the content of the manuscript.

Financial support and sponsorship

None.

Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

This study was approved by the Ethics Committee of Anyang Tumor Hospital (Approval No. 2025WZ01K01). The current manuscript is based on the same retrospectively collected, anonymized clinical dataset covered by the approved study and represents a secondary analysis with a different analytical focus. No new participants were recruited and no additional intervention or data collection was performed.

Consent for publication

Not applicable.

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