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Development and validation of a predictive nomogram for postoperative upper limb lymphedema in breast cancer patients: a retrospective cohort study

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Upper limb lymphedema is a common and debilitating complication following breast cancer surgery. Identifying patients at high risk for developing lymphedema is crucial for early intervention and improved outcomes. This study aimed to develop and validate a predictive nomogram for estimating the risk of postoperative upper limb lymphedema in breast cancer patients. A retrospective cohort of 724 breast cancer patients who underwent radical surgery was analyzed. Of these, 211 (29.1%) developed postoperative upper limb lymphedema. Baseline characteristics, including demographic, clinical, and treatment-related factors, were compared between patients with and without lymphedema. Univariate and multivariate logistic regression analyses were conducted to identify independent risk factors. A nomogram was then constructed using the significant predictors. The performance of the nomogram was evaluated through the receiver operating characteristic (ROC) curve and calibration curve analysis. In the multivariate analysis, age, body mass index (BMI), education level, hypertension, TNM stage, menopausal status, marital status, tumor diameter, number of lymph nodes dissected, postoperative radiotherapy, postoperative complications, and functional exercise were identified as independent predictors of lymphedema. The nomogram demonstrated excellent discrimination, with an area under the ROC curve of 0.944 (95% CI 0.926–0.962). The calibration curve showed good agreement between predicted and observed probabilities, indicating the model's reliability and accuracy. This study successfully developed a predictive nomogram for estimating the risk of postoperative upper limb lymphedema in breast cancer patients. The nomogram demonstrated strong predictive performance and calibration, making it a valuable tool for clinicians to identify high-risk patients and guide early interventions.

Keywords Breast cancer, Lymphedema, Nomogram, Risk prediction, Surgery

Postoperative upper limb lymphedema is a common complication in breast cancer patients, characterized by the accumulation of lymphatic fluid in the arm. It can result in swelling, pain, and impaired quality of life, affecting both physical function and psychological well-being[1–3]. The incidence of lymphedema varies widely, with studies reporting rates ranging from 4 to 49%, depending on the extent of surgery, particularly axillary lymph node dissection, the use of adjuvant therapies such as radiation, and individual patient factors[4,5].

Several risk factors for the development of lymphedema have been identified, including age, body mass index (BMI), axillary lymph node dissection, radiotherapy, and the presence of postoperative complications[6,7]. However, the interplay between these factors and their cumulative impact on lymphedema risk is complex and

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not fully understood. While some patients develop lymphedema despite minimal risk factors, others remain unaffected despite multiple high-risk characteristics. This variability highlights the need for a reliable predictive model that can estimate individual risk and guide personalized management strategies.

Nomograms have emerged as valuable tools in the field of oncology, offering individualized risk predictions based on a combination of patient and treatment-related variables[8]. These graphical tools have been successfully implemented in predicting outcomes in various cancers, but their application in the context of breast cancer-related lymphedema remains limited.

The aim of this study was to develop and validate a predictive nomogram for estimating the risk of postoperative upper limb lymphedema in breast cancer patients. By incorporating a comprehensive set of clinical and demographic variables, we sought to create a model that could accurately stratify patients according to their risk of developing lymphedema. This tool has the potential to enhance clinical decision-making, enabling early intervention and tailored surveillance strategies for high-risk individuals.

Materials and methods

Study design and population

This retrospective cohort study was conducted on 724 breast cancer patients who underwent modified radical mastectomy (MRM), which includes axillary lymph node dissection (ALND), at a tertiary hospital between July 2022 and January 2024. All patients included in the study received ALND as part of their surgical treatment. Sentinel lymph node biopsy (SLNB) alone was not performed in any case. Inclusion criteria required patients to have a histologically confirmed diagnosis of breast cancer, to have undergone complete radical mastectomy, and to have comprehensive clinical data available, including preoperative, intraoperative, and postoperative records. Exclusion criteria included patients with a prior history of upper limb lymphedema, those with bilateral breast cancer, patients who received neoadjuvant chemotherapy, and individuals with incomplete or missing clinical data relevant to the study endpoints. The study was approved by the Mianzhu City People's Hospital Ethics Committee (Ethical Approval No. 2023-K-061), and due to the retrospective nature of the research, the requirement for informed consent was waived in accordance with institutional guidelines and regulations. All methods were performed in accordance with relevant ethical standards and guidelines.

Data collection

Clinical data, including patient demographics, comorbidities, tumor characteristics, and treatment modalities, were extracted from the electronic medical records of the study participants. Postoperative complications were defined as any documented occurrence of wound infection, hematoma, seroma, or delayed wound healing. Functional exercise status was assessed based on clinical notes recorded by the nursing staff during routine postoperative follow-up visits. These notes reflected whether patients received guidance on and performed upper limb rehabilitation exercises, such as shoulder mobilization and manual lymphatic drainage techniques. The information was based on clinical documentation rather than self-report questionnaires.

Postoperative exercise was defined as regular arm and shoulder mobility training initiated within 7 days after surgery and continued for a minimum of 2 weeks, as per institutional rehabilitation guidelines. This information was retrospectively extracted from electronic medical records, including standardized nursing documentation and postoperative physician notes. Patients were categorized as "Yes" if such exercise was explicitly documented, and "No" otherwise.

The primary outcome was the development of postoperative upper limb lymphedema, defined as an increase in arm circumference of more than 2 cm compared to the preoperative baseline, consistent with the criteria established by the International Society of Lymphology (ISL). Arm circumference was measured using a standardized non-elastic measuring tape at two anatomical landmarks: 5 cm above and 5 cm below the elbow on the affected arm. All measurements were performed by trained nursing staff using a consistent protocol during routine postoperative outpatient follow-up visits. Preoperative baseline measurements were systematically conducted as part of the surgical evaluation and documented in the electronic medical records. Follow-up measurements were performed at 1, 3, 6, and 12 months postoperatively. Due to the retrospective design, blinding was not applicable; however, the use of trained personnel and standardized methods helped ensure measurement reliability. The total follow-up duration for each patient was 12 months. Patients were categorized into two groups: those who developed lymphedema (Occurrence group) and those who did not (Non-Occurrence group).

Variables and measurements

The variables considered for analysis included age, body mass index (BMI), educational level, presence of diabetes and hypertension, TNM stage, menopausal status, marital status, tumor diameter, axillary lymph node dissection extent, postoperative radiotherapy, chemotherapy, postoperative complications, and engagement in functional exercise. Age was recorded as a continuous variable, while all other variables were treated as categorical. BMI was classified as $< 24\ kg/m^2$ or $\geq 24\ kg/m^2$, and tumor diameter was categorized as ≤ 5 cm or > 5 cm. The extent of lymph node dissection was recorded as < 10 nodes or ≥ 10 nodes.

Statistical analysis

Descriptive statistics were used to summarize the baseline characteristics of the study population. Continuous variables were expressed as medians with interquartile ranges (IQRs), and categorical variables as frequencies and percentages. The chi-square test or Fisher's exact test was used for comparing categorical variables between the Occurrence and Non-Occurrence groups, while the Mann–Whitney U test was employed for continuous variables.

Univariate logistic regression analysis was performed to identify potential risk factors for postoperative upper limb lymphedema. Variables with a P value < 0.05 in the univariate analysis were included in the multivariate logistic regression model to adjust for potential confounders. Odds ratios (ORs) with 95% confidence intervals (CIs) were calculated to estimate the strength of association between each variable and the development of lymphedema.

Nomogram construction and validation

A predictive nomogram was constructed based on the significant predictors identified in the multivariate analysis. The nomogram's performance was evaluated using the receiver operating characteristic (ROC) curve, with the area under the curve (AUC) serving as a measure of the model's discriminative ability. Calibration of the nomogram was assessed by comparing the predicted probabilities with observed outcomes using a calibration curve. Internal validation was performed using bootstrap resampling with 1,000 iterations to reduce overfitting and ensure the robustness of the model.

Software

All statistical analyses were conducted using SPSS version 26.0 (IBM Corp., Armonk, NY, USA), with a two-sided P value < 0.05 considered statistically significant. The dataset had less than 5% missing data for all variables. Cases with missing values were excluded using listwise deletion during univariate and multivariate logistic regression analyses. No imputation was performed. The nomogram was constructed using R version 4.0.3 (R Foundation for Statistical Computing, Vienna, Austria), and its performance was evaluated with the ROC curve and calibration curve analysis.

Results

Baseline characteristics of patients undergoing breast cancer radical surgery and their association with postoperative upper limb lymphedema

A total of 724 patients who underwent breast cancer radical surgery were included in this study, of whom 211 (29.1%) developed postoperative upper limb lymphedema (Occurrence group), while 513 (70.9%) did not (Non-Occurrence group). The baseline characteristics of the two groups are summarized in (Table 1). Patients in the Occurrence group were significantly older than those in the Non-Occurrence group (median age: 60 [IQR 56–62] vs. 54 [IQR 51–58], P < 0.001). A higher proportion of patients in the Occurrence group had a BMI ≥ 24 kg/m^2 (67.3 vs. 51.9%, P < 0.001). Educational attainment was also associated with lymphedema risk, with 56.4% of patients in the Occurrence group having education below high school, compared to 70.8% in the Non-Occurrence group (P < 0.001). Among comorbidities, hypertension was more common in the Occurrence group (57.8 vs. 29.6%, P < 0.001), and diabetes also showed a statistically significant difference (16.6 vs. 10.7%, P = 0.040). More advanced cancer stage (TNM Stage III: 56.4 vs. 24.4%, P < 0.001), larger tumor diameter (> 5 cm: 55.5 vs. 26.7%, P < 0.001), and higher axillary lymph node involvement (≥ 10 nodes: 72.5 vs. 38.4%, P < 0.001) were significantly associated with lymphedema occurrence. Postmenopausal status (73.5 vs. 57.5%, P < 0.001), marital status (married: 82.0 vs. 68.4%, P < 0.001), receipt of radiotherapy (66.8 vs. 35.7%, P < 0.001), and presence of postoperative complications (81.5 vs. 39.2%, P < 0.001) were also more prevalent in the Occurrence group. Interestingly, a significantly higher proportion of patients in the Occurrence group reported engaging in postoperative functional exercises (82.0% vs. 41.7%, P < 0.001), possibly reflecting medical recommendations after early lymphedema detection. There were no significant differences between the groups in terms of chemotherapy status (P = 0.827) or lesion laterality (P = 0.212).

Univariate and multivariate logistic regression analyses of factors associated with postoperative upper limb lymphedema

The results from the analysis shown in Table 2 demonstrate that several factors are significantly associated with the risk of developing postoperative upper limb lymphedema in breast cancer patients. Age and BMI were both found to be significant predictors, with older age (OR 1.232, 95% CI 1.164–1.304, P < 0.001) and a BMI of ≥ 24 kg/m^2 (OR 1.897, 95% CI 1.112–3.236, P = 0.019) associated with a higher risk of lymphedema. Educational level was inversely related to lymphedema risk, where patients with less than a high school education had a lower risk (OR 0.450, 95% CI 0.261–0.774, P = 0.004). While diabetes was initially significant in univariate analysis, it did not remain so in the multivariate model (P = 0.362). However, hypertension continued to show a strong association with lymphedema (OR 2.773, 95% CI 1.652–4.655, P < 0.001). Additional factors such as advanced TNM stage, premenopausal status, larger tumor diameter (> 5 cm), lower lymph node count (< 10 nodes), receiving radiotherapy, lack of postoperative complications, and engaging in regular exercise were all identified as significant predictors of lymphedema in the multivariate analysis, with all showing strong statistical significance (P < 0.05). These findings suggest a multifactorial risk profile for postoperative lymphedema in this patient population.

Performance and validation of a predictive nomogram for postoperative upper limb lymphedema in breast cancer patients

The predictive nomogram for estimating the risk of postoperative upper limb lymphedema in breast cancer patients (Fig. 1) demonstrated robust performance, with an area under the receiver operating characteristic (ROC) curve of 0.944 (95% CI 0.926–0.962), as shown in (Fig. 2). This high AUC value indicates the model's excellent capability to differentiate between patients at high and low risk of developing lymphedema. Additionally, the calibration curve presented in Fig. 3 illustrates a strong agreement between the predicted probabilities and the actual observed outcomes. The proximity of the bias-corrected line to the ideal diagonal line underscores

Characteristics	Occurrence (N = 211)	Occurrence (%)	Non-occurrence (N = 513)	Non-occurrence (%)	P value
Age, median (IQR)	60 (56–62)	–	54 (51–58)	–	< 0.001
BMI < 24 kg/m^2	69	32.7	247	48.1	< 0.001
BMI ≥ 24 kg/m^2	142	67.3	266	51.9	
Below high school	119	56.4	363	70.8	< 0.001
High school and above	92	43.6	150	29.2	
No diabetes	176	83.4	458	89.3	0.040
Yes diabetes	35	16.6	55	10.7	
No hypertension	89	42.2	361	70.4	< 0.001
Yes hypertension	122	57.8	152	29.6	
TNM stage I	24	11.4	156	30.4	< 0.001
TNM stage II	68	32.2	232	45.2	
TNM stage III	119	56.4	125	24.4	
Premenopausal	56	26.5	218	42.5	< 0.001
Postmenopausal	155	73.5	295	57.5	
Unmarried	38	18.0	162	31.6	< 0.001
Married	173	82.0	351	68.4	
Lesion side: left	114	54.0	251	48.9	0.212
Lesion side: right	97	46.0	262	51.1	
Tumor ≤ 5 cm	94	44.5	376	73.3	< 0.001
Tumor > 5 cm	117	55.5	137	26.7	
< 10 lymph nodes	58	27.5	316	61.6	< 0.001
≥ 10 lymph nodes	153	72.5	197	38.4	
No radiotherapy	70	33.2	330	64.3	< 0.001
Yes radiotherapy	141	66.8	183	35.7	
No chemotherapy	103	48.8	255	49.7	0.827
Yes chemotherapy	108	51.2	258	50.3	
No complications	39	18.5	312	60.8	< 0.001
Yes complications	172	81.5	201	39.2	
No exercise	38	18.0	299	58.3	< 0.001
Yes exercise	173	82.0	214	41.7	

Table 1. Baseline characteristics of patients undergoing breast cancer radical surgery and their association with postoperative upper limb lymphedema. Values are presented as median (interquartile range) for continuous variables and number (percentage) for categorical variables. Percentages reflect column percentages within each subgroup. The 'Exercise' variable was derived from retrospective chart review based on documentation of postoperative rehabilitation activities in the medical record. P values were calculated using Mann–Whitney U test for age and chi-square test for categorical variables. A P value < 0.05 was considered statistically significant.

the model's reliability and accuracy, making it a valuable tool for clinical prediction of postoperative upper limb lymphedema in breast cancer patients.

Discussion

In this study, we identified several key factors associated with the risk of developing postoperative upper limb lymphedema (PULL) in breast cancer patients. Our findings revealed that older age, higher BMI, advanced TNM stage, hypertension, and the extent of axillary lymph node dissection were significantly associated with an increased risk of PULL. The predictive nomogram developed from these factors demonstrated excellent discrimination and calibration, with an AUC of 0.944, indicating its potential utility in clinical settings for identifying high-risk patients.

The association between hypertension and lymphedema, as demonstrated in our study, highlights the importance of managing blood pressure in breast cancer patients to reduce the risk of PULL. This finding is supported by the work of Brown et al. (2023), who emphasized the role of hypertension in exacerbating lymphatic dysfunction, leading to increased interstitial fluid pressure and impaired lymphatic drainage[9]. The identification of hypertension as a risk factor underscores the need for integrated management strategies that include both cancer treatment and control of comorbid conditions to minimize lymphedema risk.

Age and BMI were also significant predictors in our analysis, aligning with the findings of Shen et al. (2024), who reported that older age and higher BMI are critical factors in the development of breast cancer-related lymphedema (BCRL)[7]. These results suggest that weight management and careful monitoring of older patients

Characteristics	Total (N)	Univariate analysis		Multivariate analysis	
		Odds ratio (95% CI)	P value	Odds ratio (95% CI)	P value
Age	724	1.229 (1.181–1.279)	<**0.001**	1.232 (1.164–1.304)	<**0.001**
BMI	724				
< 24 kg/m^2	316	Reference		Reference	
≥ 24 kg/m^2	408	1.911 (1.366–2.673)	<**0.001**	1.897 (1.112–3.236)	**0.019**
Education	724				
High school and above	242	Reference		Reference	
Below high school	482	0.534 (0.383–0.745)	<**0.001**	0.450 (0.261–0.774)	**0.004**
Diabetes	724				
No	634	Reference		Reference	
Yes	90	1.656 (1.047–2.618)	**0.031**	1.428 (0.664–3.071)	0.362
Hypertension	724				
No	450	Reference		Reference	
Yes	274	3.256 (2.335–4.540)	<**0.001**	2.773 (1.652–4.655)	<**0.001**
TNM_Stage	724				
Stage III	244	Reference		Reference	
Stage II	300	0.308 (0.213–0.445)	<**0.001**	0.356 (0.201–0.633)	<**0.001**
Stage I	180	0.162 (0.098–0.266)	<**0.001**	0.165 (0.079–0.342)	<**0.001**
Menopause	724				
Yes	450	Reference		Reference	
No	274	0.489 (0.344–0.695)	<**0.001**	0.535 (0.308–0.928)	**0.026**
Marriage	724				
Married	524	Reference		Reference	
Unmarried	200	0.476 (0.320–0.708)	<**0.001**	0.547 (0.300–1.000)	0.050
Tumor_Diameter	724				
≤ 5 cm	470	Reference		Reference	
> 5 cm	254	3.416 (2.445–4.774)	<**0.001**	4.104 (2.397–7.026)	<**0.001**
Lymph_Nodes	724				
≥ 10 nodes	350	Reference		Reference	
< 10 nodes	374	0.236 (0.166–0.336)	<**0.001**	0.297 (0.175–0.504)	<**0.001**
Radiotherapy	724				
No	400	Reference		Reference	
Yes	324	3.632 (2.589–5.097)	<**0.001**	3.675 (2.192–6.162)	<**0.001**
Complications	724				
Yes	373	Reference		Reference	
No	351	0.146 (0.099–0.216)	<**0.001**	0.177 (0.101–0.307)	<**0.001**
Exercise	724				
No	337	Reference		Reference	
Yes	387	6.361 (4.296–9.419)	<**0.001**	6.191 (3.496–10.965)	<**0.001**

Table 2. Univariate and multivariate logistic regression analyses of factors associated with postoperative upper limb lymphedema. This table presents the results of univariate and multivariate logistic regression analyses identifying factors associated with the risk of postoperative upper limb lymphedema in breast cancer patients. Odds ratios (OR) and 95% confidence intervals (CI) are reported for each factor, with corresponding P values indicating statistical significance. BMI (body mass index) categories are defined as < 24 and ≥ 24 kg/m^2. TNM staging refers to the tumor-node-metastasis classification, with Stage I, II, and III representing the progression of cancer. The reference category is indicated for each variable, serving as the baseline for comparison. Variables found to be statistically significant in the multivariate analysis ($P < 0.05$) are considered independent risk factors for developing postoperative upper limb lymphedema.

are essential components of lymphedema prevention strategies. The influence of BMI on lymphedema risk may be attributed to increased lymphatic load and reduced drainage capacity in patients with higher body mass.

The extent of ALND, particularly the removal of a higher number of lymph nodes, was another significant factor identified in our study. This finding is consistent with the work of Lin et al. (2022) and Bevilacqua et al. (2012), who identified ALND as a major risk factor for lymphedema due to the disruption of lymphatic pathways[10,11]. The inclusion of radiotherapy as a significant predictor further highlights the compounded risk posed by multiple treatment modalities, as demonstrated in studies by Li et al. (2023) and Martínez-Jaimez et al.

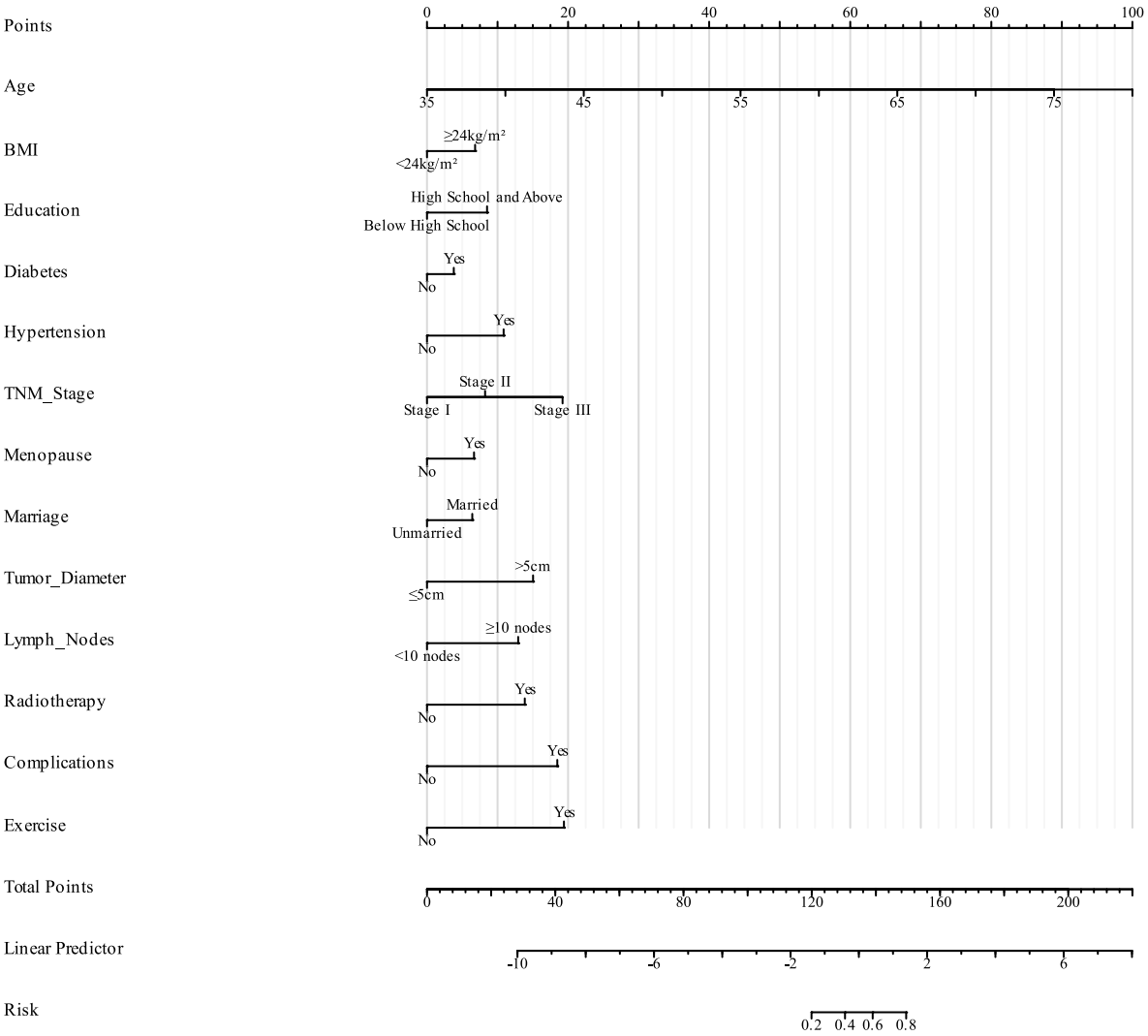

Fig. 1. Nomogram for predicting postoperative upper limb lymphedema. The nomogram is constructed based on multiple predictors including age, BMI, education level, diabetes status, hypertension, TNM stage, menopausal status, marital status, tumor diameter, number of lymph nodes, radiotherapy, postoperative complications, and exercise. Each predictor contributes to a total score that corresponds to the predicted probability of developing upper limb lymphedema postoperatively.

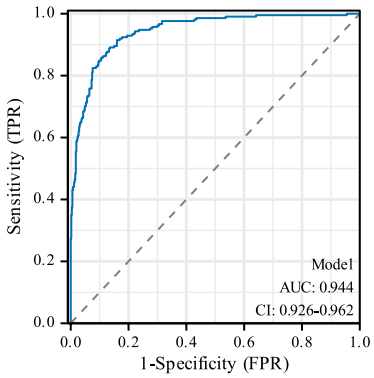

Fig. 2. ROC Curve for the diagnostic model of postoperative upper limb lymphedema. The receiver operating characteristic (ROC) curve illustrates the diagnostic accuracy of the predictive model for upper limb lymphedema, with an area under the curve (AUC) of 0.944, indicating excellent discrimination capability. The 95% confidence interval (CI) ranges from 0.926 to 0.962.

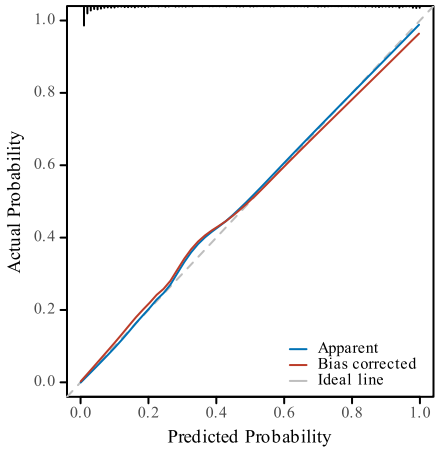

Fig. 3. Calibration curve of the predictive model. The calibration curve assesses the agreement between predicted probabilities and observed outcomes for postoperative upper limb lymphedema. The curve demonstrates good calibration, indicating that the model's predictions are consistent with actual clinical outcomes.

(2022)[12,13]. The combined effect of surgery and radiotherapy on lymphatic injury underscores the importance of considering less invasive approaches and the potential benefits of axillary-sparing techniques.

Interestingly, our results showed that patients with lower educational levels (below high school) had a lower risk of developing postoperative lymphedema, which contrasts with findings from several prior studies[14–16]. One possible explanation is that patients with lower education levels in our cohort may have had more physical rest postoperatively or were more closely supervised by caregivers, reducing strain on the lymphatic system. Alternatively, this unexpected association may be due to residual confounding or selection bias inherent in the retrospective design. Further prospective studies are warranted to clarify this relationship and investigate potential sociobehavioral mediators. These findings underscore the need for targeted educational interventions to mitigate the impact of socioeconomic disparities on lymphedema risk, emphasizing the importance of tailored support programs that address the specific needs of less-educated patients.

Finally, the paradoxical finding that postoperative exercise was associated with an increased risk of lymphedema highlights the critical importance of individualized exercise regimens for breast cancer survivors. While physical activity is generally advocated to enhance lymphatic function and overall recovery, the studies by Cormie et al. (2013)[17], Hayes et al. (2009)[18], and Schmitz et al. (2009)[19] suggest that the type, intensity, and timing of exercise are pivotal in determining its effects on lymphedema. Cormie et al. (2013) demonstrated that both high-load and low-load resistance exercises can be safely performed by women with breast cancer-related lymphedema (BCRL) without exacerbating symptoms. However, the study emphasized the necessity of appropriate supervision and prescription, as the risk of lymphedema worsening could increase if exercise is not carefully managed. Similarly, Hayes et al. (2009) found that a mixed-type exercise program, including aerobic and resistance training, did not worsen lymphedema and even showed potential benefits in physical and psychosocial outcomes, suggesting that a well-structured exercise regimen is essential. In contrast, Schmitz et al. (2009) highlighted that progressive weight lifting, when carefully controlled and accompanied by the use of compression garments, did not increase limb swelling and was associated with reduced lymphedema exacerbations. This finding underscores the need for personalized exercise programs that consider the specific needs and conditions of each patient, balancing the benefits of exercise with the potential risks. These studies collectively indicate that while exercise is beneficial, it must be tailored to the individual to prevent adverse outcomes. The need for further research is clear, particularly to establish specific exercise protocols that optimize lymphatic function without increasing the risk of lymphedema, ensuring that all patients can safely benefit from physical activity during their recovery.

While this study provides significant insights into the risk factors for postoperative upper limb lymphedema (PULL) in breast cancer patients, several limitations should be acknowledged. Firstly, the retrospective design may introduce recall bias and limits the ability to establish causal relationships. The study population was derived from a single institution, which may limit the generalizability of the findings to broader, more diverse populations. Additionally, certain variables, such as the type and intensity of postoperative exercise, were not standardized, potentially affecting the accuracy of the results. Another limitation is the lack of long-term follow-up data, which restricts the ability to assess the persistence of lymphedema over time and the impact of evolving treatment protocols. Lastly, while we included several relevant clinical and demographic factors, the potential influence of genetic predispositions and specific treatment-related variables, such as the exact radiation dose, were not evaluated, which could provide further insights into the risk profile for PULL. Future studies should address these limitations by incorporating prospective designs, diverse patient populations, and more comprehensive variable assessments to validate and expand upon our findings.

Despite the excellent performance of the nomogram, we acknowledge the potential for overfitting given the retrospective, single-center design and the use of internal validation alone. Although bootstrap resampling (1000

iterations) was employed to enhance model reliability and minimize overfitting, the lack of external validation limits the generalizability of our findings. Future studies should aim to externally validate this nomogram using independent cohorts from multiple institutions to confirm its applicability across diverse patient populations and clinical settings. While several of the predictors identified in this study—such as tumor size, body mass index, and lymph node dissection—have been previously reported as risk factors for lymphedema, the value of our work lies in its integration of these established and less frequently explored variables, including education level, menopausal status, and postoperative functional exercise, into a single, individualized predictive model. This nomogram, supported by a high AUC (0.944), provides a practical and visual tool for clinicians to assess patient-specific risk and tailor early preventive strategies.

Additionally, we acknowledge that the retrospective study design introduces inherent limitations such as potential selection bias, misclassification, and inconsistencies in data collection, particularly for variables like functional exercise and postoperative complications. To minimize these biases, all data were extracted from standardized electronic medical records, and lymphedema was assessed using predefined measurement criteria at scheduled postoperative intervals. Functional exercise status was determined from structured nursing documentation during routine follow-up, rather than self-report or recall. Nonetheless, we have noted this limitation clearly and emphasized the need for prospective multicenter validation to enhance the reliability and generalizability of our findings.

In conclusion, our study provides valuable insights into the multifactorial nature of PULL in breast cancer patients. The predictive nomogram we developed offers a reliable tool for clinical decision-making, enabling the identification of high-risk patients and the implementation of personalized preventive strategies. Future research should focus on the external validation of our model across diverse populations and the exploration of potential pharmacological interventions for lymphedema prevention.

Data availability

The datasets generated and analyzed during the current study are not publicly available due to patient confidentiality and institutional regulations. However, they are available from the corresponding author, Tao Yi, upon reasonable request.

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Author contributions

Xuemei Luo and Jianrui Ye contributed equally to this work as co-first authors. Xuemei Luo led the design and implementation of the research, data collection, and the initial drafting of the manuscript. Jianrui Ye played a key role in the statistical analysis, interpretation of the results, and manuscript revision. Ting Xiao was responsible for the coordination of clinical data collection and provided critical input on the rehabilitation aspects of the study. Hu Jun contributed to the interpretation of the clinical significance of the findings and manuscript editing. Tao Yi, as the corresponding author, supervised the entire project, guided the study design, and ensured the accuracy and integrity of the work. All authors read and approved the final manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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