

Development of a Predictive Model for the Risk of RLRI Following Radical Radiotherapy for Cervical Cancer Using a Lasso-Logistic Regression Model

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Article

Keywords: locally advanced cervical cancer, curative radiotherapy, chronic radiation-induced rectal injury, dose-volume parameters, contour plots, predictive models

Posted Date: October 4th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10179784/v1>

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Additional Declarations: No competing interests reported.

Abstract

Background Cervical cancer is one of the most common cancers among women worldwide. Although curative radiotherapy can significantly improve the prognosis of patients with locally advanced disease, Radiation-induced Late Rectal Injury (RLRI) severely compromises patients' long-term quality of life.

Objective To investigate risk factors for Grade ≥ 2 RLRI in patients with locally advanced cervical cancer following curative radiotherapy, and to construct and validate a nomogram model.

Methods This study included 287 patients who underwent radical radiotherapy for locally advanced cervical cancer at two Grade A tertiary hospitals in Qinghai between May 2020 and May 2025. Demographic data, underlying medical conditions, clinical and pathological information, and rectal dose-volume histogram (DVH) parameters were collected. According to Section 7.3, the data was randomly divided into a training cohort of 204 cases and a validation cohort of 83 cases. Screen for variables with $P < 0.1$ using univariate logistic regression, Lasso regression reduces dimensionality and addresses multicollinearity, Multi-factor Logistic Regression (backward method) to identify independent predictors and build a nomogram model; Use the receiver operating characteristic (ROC) curve, area under the curve (AUC), the Hosmer-Lemeshow test, calibration curves, and decision curve analysis (DCA) to evaluate the model.

Results The training set included 47 cases with $\geq$ Grade 2 RLRI (23.04%), and the validation set included 17 cases (20.48%). After filtering using Lasso regression, five variables were identified: hypertension, type 2 diabetes, Dmax, D2cc, and D1cc. These variables were included in a multivariate logistic regression analysis, which ultimately identified hypertension, Dmax, and D2cc as three independent risk factors. A corresponding nomogram model was then constructed based on these findings. The AUC for the training cohort was 0.846 (95% CI: 0.782–0.910), and the AUC for the validation cohort was 0.772 (95% CI: 0.648–0.895), indicating good discriminatory power. The Hosmer-Lemeshow tests for the training and validation cohorts were $\chi^2 = 11.26$, $P = 0.258$, and $\chi^2 = 8.28$, $P = 0.505$, respectively, indicating that the models fit the data well; The calibration curves for the training and validation cohorts align with the ideal diagonal, indicating that the model is well calibrated. The DCA results show that within the 0–0.7 risk threshold range, the model demonstrates a significant net profit advantage.

Conclusion A nomogram model based on hypertension, Dmax, and D2cc can intuitively predict the risk of severe RLRI following radiation therapy for locally advanced cervical cancer, and may provide guidance for dose constraints on the rectum as a critical organ and for early intestinal protection.

Introduction

Cervical cancer is one of the most common gynecological cancers among women worldwide; its incidence rate is second only to colorectal cancer, and it is also the fourth most common cancer and the fourth leading cause of cancer-related deaths among women.[1–3] Radiation therapy, as one of the key treatment options for cervical cancer, is particularly suitable for patients with locally advanced cervical

cancer[4].However, radiation therapy is also associated with certain side effects, including radiation-induced damage to organs such as the rectum, small intestine, colon, and bladder, as well as hematological toxicity. Among these, radiation-induced rectal damage is the most common and intractable [5–7], which negatively impacts patients' quality of life. Therefore, this study focuses on locally advanced cervical cancer and constructs a predictive model based on its risk factors, with the aim of providing data to inform the optimization of intestinal dose limits when designing radiotherapy treatment plans in clinical practice.

Materials and Methods

1.1 Research subjects

The study included 287 patients who underwent radiotherapy for cervical cancer and were admitted to the Qinghai Red Cross Hospital and the Affiliated Hospital of Qinghai University between May 2020 and May 2025. Inclusion Criteria: ☐ Pathologically confirmed locally advanced cervical cancer staged as ☐B3, ☐A2–☐A according to the FIGO 2018 classification; ☐ Patients who underwent radical radiotherapy or concurrent chemoradiotherapy; ☐ Patients who had not previously received pelvic or abdominal radiotherapy; ☐ Complete clinical data, radiation treatment plans, and follow-up records. Exclusion criteria: ☐ History of inflammatory bowel disease prior to radiation therapy; ☐ Concurrent malignant tumors or intestinal metastases; ☐ Follow-up period < 1 year; ☐ Interruption of radiation therapy for other reasons. This retrospective clinical study was reviewed and approved by the Institutional Review Board of Qinghai Red Cross Hospital (Full name: Institutional Review Board of Qinghai Red Cross Hospital, Approval No. XHKL-2025-032). The requirement for written informed consent was formally waived by the committee, since all patient clinical data were fully anonymized without disclosure of personal identifiable information, and the research would not bring extra physical or psychological risks to enrolled patients. All study procedures followed the Declaration of Helsinki.

1.2 Radiation Therapy Methods

Based on the patient's clinical condition, thermoplastic film fixation was performed, followed by CT simulation for positioning and the development of a radiation therapy plan. All patients received IMRT treatment using a 6-MV X-ray linear accelerator, with a prescribed dose of 45–50.4 Gy in 25–28 fractions, 1.8–2.0 Gy/fraction, five times per week. If pelvic lymph nodes were positive, the dose was simultaneously escalated to 60 Gy in 25–28 fractions, at 2.14–2.4 Gy per fraction. Volume fractions (V5, V10, V20, V30, V40, V45, V50) of the rectum exposed to $\geq 5, 10, 20, 30, 40, 45,$ and 50 Gy were determined using dose-volume histograms. During external beam radiation therapy, cisplatin 40 mg/m² was administered once weekly for a total of 4–6 doses. Following completion of external beam radiation therapy, brachytherapy was administered using an Ir-192 high-dose-rate afterloader. Prior to treatment, CT simulation was performed to delineate the high-risk clinical target volume and critical organs; the prescribed dose was 28–30 Gy over 4–5 fractions, at 6–7 Gy per fraction. Dose-volume histograms were

used to determine the minimum dose received within rectal volumes of 2 cm³, 1 cm³, and 0.1 cm³ (D2cc, D1cc, and D0.1cc).

1.3 Diagnostic Criteria and Grading of Chronic Radiation-Induced Rectal Injury

Cases meeting the diagnostic criteria for radiation-induced rectal injury outlined in the “Chinese Multidisciplinary Expert Consensus on the Diagnosis and Treatment of Radiation-Induced Rectal Injury (2021 Edition)”[8], and graded according to the TROG/EORTC criteria for radiation-induced rectal injury[9], where Grade 0 is asymptomatic. Grade 1: mild diarrhea, mild cramping, and mild increase in rectal discharge or bleeding in the stool. Grade 2: Moderate diarrhea and intestinal colic, with > 5 bowel movements per day, copious rectal mucus, or intermittent bleeding. Grade 3: Obstruction or bleeding requiring surgery. Grade 4: Intestinal wall perforation, necrosis, or fistula formation. If the patient’s symptoms recur for more than three months or if new symptoms develop more than three months after the completion of radiation therapy, the severity is recorded and graded based on the most severe episode of toxicity.

1.4 Follow-up and Observation Measures

☒ Collection of clinical data: age, BMI, FIGO stage, histological type, tumor size, hypertension, diabetes, and history of abdominal and pelvic surgery.☒ Collection of dose-volume parameters: Dmax, Dmean (Gy), V5, V10, V20, V30, V40, V45, V50 (%), and D0.1cc, D2cc (Gy).

1.5 Statistical Methods

Data analysis was performed using SPSS 28.0 and R 4.4.3. Descriptive analysis: Continuous variables are expressed as mean ± standard deviation; t-tests were used for comparisons between groups. If data did not follow a normal distribution, they were expressed as median and interquartile range, and Mann-Whitney U tests were used for comparisons between groups. Categorical variables are expressed as frequencies and percentages; chi-square tests were used for comparisons between groups. The dataset was randomly split into a training set and a validation set in a 7:3 ratio. After screening potential predictors in the training set using univariate logistic regression, candidate independent variables with $P < 0.1$ were included in Lasso regression. The optimal lambda value was determined using 10-fold cross-validation. At the optimal lambda value, variables with non-zero coefficients were selected for multivariate logistic regression to build a predictive model. Scatter plots were plotted, and the risk prediction model was evaluated using ROC curves, AUC, calibration curves, DCA to evaluate the risk prediction model, with a significance level of $\alpha = 0.05$.

Results

2.1 Baseline Features

This study included a total of 287 cervical cancer patients who met the inclusion and exclusion criteria. They were randomly divided into a training set (n = 204) and a validation set (n = 83) in a 7:3 ratio; Based on the occurrence of $\geq$ Grade 2 RLRI, the training set was divided into an RLRI group (47 patients) and a non-RLRI group (157 patients), while the validation set was divided into an RLRI group (17 patients) and a non-RLRI group (66 patients). Demographic, clinical-pathological, and rectal dosimetric parameters were compared between the two groups in each set, as shown in Tables 1 and 2.

Table 1
General Clinical Information on Enrolled Patients

Variable	Training		Validation		χ^2	P
	N = 204		N = 83			
	RLRI	Non-RLRI	RLRI	Non-RLRI		
	n = 47	n = 157	n = 17	n = 66		
age					0.814	0.666
<40	7(14.8)	15(9.5)	1(5.8)	5(7.5)		
40–60	26(55.4)	103(65.6)	13(76.5)	43(65.2)		
>60	14(29.8)	39(24.9)	3(17.7)	18(27.3)		
BMI					0.336	0.562
≤ 24	25(53.2)	96(61.2)	10(58.8)	35(53.1)		
>24	22(46.8)	61(38.8)	7(41.2)	31(46.9)		
Hypertension					3.169	0.075
Yes	18(38.3)	34(21.7)	2(11.7)	12(18.2)		
No	29(61.7)	123(78.3)	15(88.2)	54(81.8)		
T2DM					4.816	0.028
Yes	10(21.3)	17(10.8)	4(23.5)	8(12.2)		
No	37(78.7)	140(89.2)	13(76.5)	58(87.8)		
surgical					0.101	0.751
Yes	21(46.6)	57(36.3)	2(11.7)	28(42.5)		
No	26(55.4)	100(63.7)	15(88.3)	38(57.5)		
FIGO					0.022	0.883
≤Ⅱ	14(29.7)	55(35.1)	7(41.2)	16(24.3)		
≥Ⅱ	33(70.3)	102(64.9)	10(58.8)	50(75.7)		
Pathological_type					3.517	0.172
SCC	44(93.6)	148(94.2)	15(88.3)	65(98.5)		
ADC	1(2.1)	8(5.1)	2(11.7)	1(1.5)		
ASC	2(4.3)	1(0.7)	0(0.0)	0(0.0)		
Tumor_size					0.586	0.444

Variable	Training		Validation		χ^2	P
	N = 204		N = 83			
	RLRI n = 47	Non-RLRI n = 157	RLRI n = 17	Non-RLRI n = 66		
<4cm	17(36.2)	68(43.4)	6(35.3)	24(36.4)		
≥ 4cm	30(63.8)	89(56.6)	11(64.7)	42(63.6)		
LNM					0.085	0.770
Yes	19(40.5)	60(38.3)	8(47.1)	33(50.0)		
No	28(59.5)	97(61.7)	9(52.9)	33(50.0)		
CCRT					2.059	0.151
Yes	47(100.0)	151(96.2)	17(100.0)	65(98.5)		
No	0(0.0)	6(3.8)	0(0.0)	1(1.5)		

Table 2
Rectal Radiation Dose Parameters

Variable	Median (IQR)	Range	Z	P
Dmax(Gy)	54.0(5.12)	19.4–67.8	–2.897	0.004
Dmean(Gy)	46.9(7.45)	16.7–62.9	–2.429	0.015
V5(%)	100(0.00)	0.0–100.0	–0.886	0.387
V10(%)	100(1.91)	0.0–100.0	–0.241	0.809
V20(%)	99.9(5.52)	0.0–100.0	–0.502	0.616
V30(%)	96.4(12.36)	0.0–100.0	–1.099	0.272
V40(%)	89.1(19.25)	0.0–100.0	–1.570	0.116
V45(%)	78.8(31.22)	0.0–100.0	–1.276	0.202
V50(%)	42.4(28.01)	0.0–100.0	–2.104	0.035
D2cc(Gy)	72.7(12.15)	26.4–91.6	–7.916	<0.001
D1cc(Gy)	76.1(11.52)	30.6–96.0	–7.566	<0.001
D0.1cc(Gy)	80.1(11.29)	33.5–100.0	–6.864	<0.001

2.2 Univariate Logistic Regression Analysis of Chronic Rectal Injuries Grade ≥ 2

The training set included 47 patients in the RLRI group and 157 in the non-RLRI group. Univariate analysis indicated that hypertension, diabetes, V40, V45, Dmax, Dmean, D2cc, D1cc, and D0.1cc were potential risk factors for Grade ≥ 2 chronic rectal injury following radical radiotherapy for cervical cancer ($P < 0.1$); No statistically significant differences were observed for age, BMI, FIGO stage, histological type, tumor size, history of abdominal or pelvic surgery, CCRT, V5, V10, V20, V30, or V50 ($P > 0.1$); see Table 3.

Table 3
Univariate Logistic Regression Analysis of Chronic Rectal Injuries Grade ≥ 2

Variable	B	SE	OR	CI	Z	P
age	-0.011	0.283	0.99	0.57–1.72	-0.04	0.968
BMI	0.326	0.335	1.38	0.72–2.67	0.972	0.331
Hypertension	0.809	0.357	2.25	1.12–4.52	2.265	0.024
T2DM	0.736	0.436	2.09	0.89–4.91	1.689	0.091
surgical	0.349	0.337	1.42	0.73–2.74	1.034	0.301
FIGO	0.24	0.36	1.27	0.63–2.57	0.666	0.506
Pathological_type	0.389	0.35	1.48	0.74–2.93	1.109	0.267
Tumor_size	0.299	0.344	1.35	0.69–2.65	0.87	0.384
LNМ	0.093	0.34	1.1	0.56–2.14	0.273	0.785
CCRT	15.399	979.61	4871615.65	0-Inf	0.016	0.987
Dmax	0.099	0.031	1.1	1.04–1.17	3.21	0.001
Dmean	0.078	0.031	1.08	1.02–1.15	2.504	0.012
V5	0.025	0.041	1.03	0.95–1.11	0.61	0.542
V10	0.025	0.032	1.03	0.96–1.09	0.786	0.432
V20	0.027	0.024	1.03	0.98–1.08	1.118	0.264
V30	0.028	0.017	1.03	0.99–1.06	1.635	0.102
V40	0.017	0.008	1.02	1-1.03	2.174	0.03
V45	0.012	0.006	1.01	1-1.02	1.808	0.071
V50	0.008	0.007	1.01	0.99–1.02	1.214	0.225
D2cc	0.175	0.034	1.19	1.11–1.27	5.105	<0.001
D1cc	0.165	0.032	1.18	1.11–1.26	5.2	<0.001
D0.1cc	0.117	0.024	1.12	1.07–1.18	4.941	<0.001

2. 3 Lasso Regression: Selecting Predictor Variables

This study included the nine significant variables ($P < 0.1$) identified in the univariate analysis in a Lasso regression for further screening. After 10-fold cross-validation, the λ value ($\text{lambda.min} = 0.000315$) corresponding to the minimum cross-validation error was identified as the optimal solution. Based on the non-zero coefficients, the following variables were selected: hypertension, diabetes, Dmax, D2cc, D1cc as the five predictive variables based on non-zero coefficients. The screening process is shown in Figs. 1A and 1B.

2.4 Multivariate Logistic Regression and Model Building

Based on Lasso regression, five variables were selected as candidate independent variables. With the occurrence of Grade ≥ 2 RLRI as the dependent variable, a multivariate logistic regression analysis was constructed using the backward stepwise method. The model inclusion criterion was set at $\alpha = 0.05$; ultimately, only hypertension, Dmax, and D2cc were retained in the model (Table 4). A scatterplot model predicting Grade ≥ 2 RLRI was created based on the above predictor variables for visualization (Fig. 2). Each variable is marked with a red dot on the scoring axis; the dot corresponds to the scoring value for that variable. By summing the scores of all variables to calculate a total score, a vertical line is drawn downward from the total score axis to indicate the predicted probability of developing Grade ≥ 2 RLRI in patients undergoing radical radiotherapy for cervical cancer (Fig. 3).

Table 4 Multivariate Logistic Regression Analysis of Chronic Rectal Injuries Grade ≥ 2						
Variable	B	SE	OR	CI	Z	P
Hypertension	0.897	0.422	2.452	1.072–5.608	2.126	0.034
Dmax	0.085	0.037	1.089	1.013–1.171	2.297	0.024
D2cc	0.174	0.036	1.190	1.109–1.277	4.833	<0.001

2.5 Predictive Model Evaluation and Validation

Based on the five candidate variables selected through Lasso regression, this study used backward stepwise logistic regression to construct a predictive model. Model performance was evaluated in both the training and validation sets across three dimensions—discriminatory power, calibration, and clinical net benefit—to comprehensively validate the model’s predictive performance, accuracy, and clinical utility.

The AUC for the training set was 0.846 (95% CI: 0.782–0.910), with a sensitivity of 75.2% and a specificity of 83.0%, indicating good discriminatory power (Fig. 4A); the results of the Hosmer-Lemeshow goodness-of-fit test showed $\chi^2 = 11.26$, $P = 0.258$, indicating that the model fits the data well. A calibration curve was plotted using 1,000 bootstrap resamples; the calibration curve closely aligned

with the ideal reference line, suggesting good consistency between the predicted risk of injury and the actual incidence rate (Fig. 4B). DCA results showed that within the risk threshold range of 0–0.70, the model demonstrated a significant net benefit (Fig. 4C).

Discussion

Concurrent chemoradiotherapy, as the primary treatment for locally advanced cervical cancer, has significantly improved treatment outcomes and increased survival rates in patients with cervical cancer [10, 11]. However, RLRI following radiotherapy is a key complication that limits treatment tolerance and affects long-term quality of life; severe injury can lead to recurrent bleeding and intestinal obstruction, and some patients require surgical intervention, thereby increasing the burden on the healthcare system [12, 13]. Acute radiation-induced rectal injury typically presents with diarrhea and a sensation of anal heaviness during radiation therapy; in most cases, these symptoms can be alleviated in the short term with symptomatic and supportive treatment. In contrast, RLRI of grade 2 or higher usually progresses slowly 3 months after the completion of radiation therapy, with the disease course lasting from several months to several years. Typical manifestations include rectal mucosal fibrosis, vascular malformations, recurrent rectal bleeding, intractable abdominal pain, and severe disruption of bowel habits. Conservative treatment has limited efficacy; severe cases may develop intestinal perforation or rectovaginal fistula, which not only significantly reduce patients' quality of life but also induce psychological issues such as anxiety and depression. In long-term follow-up, the quality-of-life scores for these patients are significantly lower than those of individuals without intestinal injury [14–16]. This study integrated underlying medical conditions with three-dimensional rectal dose parameters to construct and internally validate a nomogram model capable of individually predicting RLRI of grade ≥ 2 . The model demonstrated ideal discrimination, calibration, and clinical utility.

This study found that D2cc, Dmax, and hypertension were associated with the occurrence of Grade ≥ 2 RLRI following radical radiotherapy for cervical cancer, and that D2cc demonstrated the best predictive performance. D2cc represents the minimum dose within a 2 cm³ volume of the rectum and reflects local high-dose hotspots in the rectum; afterloading brachytherapy significantly increases the local peak dose in the rectum. High-dose radiation causes sustained damage to the microvasculature and smooth muscle in the submucosal layer of the rectum, leading in the long term to mucosal fibrosis, chronic ulcers, and bleeding from vascular malformations. Numerous domestic and international studies on 3D afterloading dosimetry for cervical cancer have confirmed that rectal D2cc is significantly positively correlated with late rectal toxicity; as D2cc increases by a certain dose, the risk of severe chronic rectal damage rises accordingly [17, 18], which is highly consistent with the results of our multivariate regression analysis showing D2cc with an OR of 1.190 ($P < 0.001$). When developing radiation therapy treatment plans in a clinical setting, priority should be given to strictly limiting the rectal D2cc dose by optimizing the position of the afterloader and adjusting the weighting of external beam radiation, thereby reducing local high-dose hotspots in the rectum and lowering the risk of severe long-term intestinal damage. Dmax represents the peak radiation dose at a single point in the rectal tissue and reflects the maximum radiation burden borne by the full thickness of the rectal tissue. Even if the average rectal

dose, V5, V50, and other low-volume dose parameters meet the standards, if Dmax exceeds the safety threshold, it will still synergize with D2cc to amplify the effects of late radiation damage to the rectum. Long-term hypertension is a clinical risk factor independent of dose parameters. This study shows that patients with hypertension have a 2.452-fold higher risk of developing Grade ≥ 2 chronic RLRI compared to those without hypertension (OR = 2.452, 95% CI: 1.072–5.608, P = 0.034). Long-term hypertension causes thickening of the walls of small arteries throughout the body, narrowing of the vascular lumen, and decreased vascular elasticity, resulting in a state of chronic low perfusion and insufficient reserve in the rectal mucosal microcirculation. Ionizing radiation further damages the endothelial barrier of rectal microvessels, inhibits angiogenesis and the ability to repair damaged mucosa, creating a “double blow” of “vascular sclerosis + radiation-induced endothelial injury,” which increases the likelihood of chronic mucosal ischemia, erosion, and persistent bleeding[12, 13, 19, 20]. For patients with hypertension undergoing radiotherapy, blood pressure must be strictly controlled throughout the entire treatment course, and measures to protect the rectum from radiation exposure should be strengthened. In univariate analysis, type 2 diabetes showed a marginally significant positive trend [20], but it was not included in the final model. This is likely due to multicollinearity with hypertension and the small number of positive cases for diabetes; further validation could be conducted in a larger, multicenter cohort.

This study still has several limitations that need to be addressed in future research: First, this study is a retrospective cohort study conducted at two Grade A tertiary hospitals in Qinghai Province. The sample was limited to the plateau region; due to differences in dietary habits, the prevalence of underlying diseases, and variations in radiotherapy equipment and treatment regimens among regional populations, there are certain limitations to extrapolating the model to different regions nationwide and to populations in lowland areas; Additionally, internal validation was performed using only a 7:3 random split, and no independent, multicenter validation using external datasets was conducted; the model's external generalization performance requires further confirmation through prospective multicenter studies. Second, there were certain omissions in the inclusion of variables. This study only included demographic factors, underlying comorbidities, tumor pathology, and rectal DVH dosimetric indicators; it did not collect data on the use of intestinal protective medications throughout the course of radiotherapy, dietary patterns, baseline intestinal discomfort symptoms, long-term nutritional status, or stratified data on blood glucose/ blood pressure control. Consequently, the study cannot quantify the confounding effects of these factors on chronic radiation-induced rectal injury, and selection bias and residual confounding may be present. Third, the study did not utilize an external independent cohort for model validation, nor did it conduct a prospective controlled intervention trial based on this nomogram. Consequently, it is currently impossible to confirm that stratified interventions based on the model can effectively reduce the actual incidence of Grade ≥ 2 chronic radiation-induced rectal injury, and the level of evidence for clinical intervention remains limited. Future prospective multicenter studies could be conducted to expand the sample size, incorporate additional clinical variables, further optimize the model, and complete external validation.

In summary, the nomogram-based predictive model developed in this study, which incorporates hypertension, Dmax, and D2cc, can effectively predict the risk of grade ≥ 2 RLRI following radical radiotherapy for locally advanced cervical cancer. Both the training and validation sets demonstrated good discriminatory power, calibration, and clinical net benefit. With readily available indicators and ease of use, this model can be employed for rapid screening of high-risk patients following radiotherapy, guiding clinicians in optimizing dose limits for the rectum as a critical organ and implementing individualized bowel protection interventions to reduce the incidence of chronic radiation-induced rectal injury.

Abbreviations

RLRI	
Radiation-induced Late Rectal Injury	
DVH	
dose-volume histogram	
ROC	
receiver operating characteristic	
AUC	
area under the curve	
DCA	
decision curve analysis	

Declarations

Data availability

All data generated or analysed during this study are included in this published article and its supplementary information files.

Acknowledgements

Not applicable.

Declaration of interests

All authors declare that they have no conflicts of interest.

Consent for publication

Not applicable.

Funding

Not applicable.

Contributions

Huixing Lu: Conceptualization, Methodology, Formal statistical analysis, Writing – original draft; collected partial clinical and dosimetric data, constructed and validated the nomogram prediction model. Hulin Liu: Radiotherapy plan review, quality control of dose-volume data, manuscript language polishing. Ting Lu: Case enrollment, sorting demographic and pathological data, univariate and Lasso regression variable screening. Fuqing Li: Radiotherapy plan review, quality control of dose-volume data, manuscript language polishing. Kuan Zhang: Supervision, project administration, study design revision, Writing – review & editing; reviewed and approved the final submitted manuscript.

Ethics declarations

Ethics approval and consent to participate

This study was approved by the hospital's Medical Ethics Committee (Approval No.: KY-2025-169). Since this study is a retrospective analysis, patient informed consent was waived following review and approval by our institution's ethics committee. All patient information was fully de-identified before data extraction to protect individual privacy.

Consent for publication

Not applicable.

Competing interests

All authors declare no conflicts of interest.

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Figures

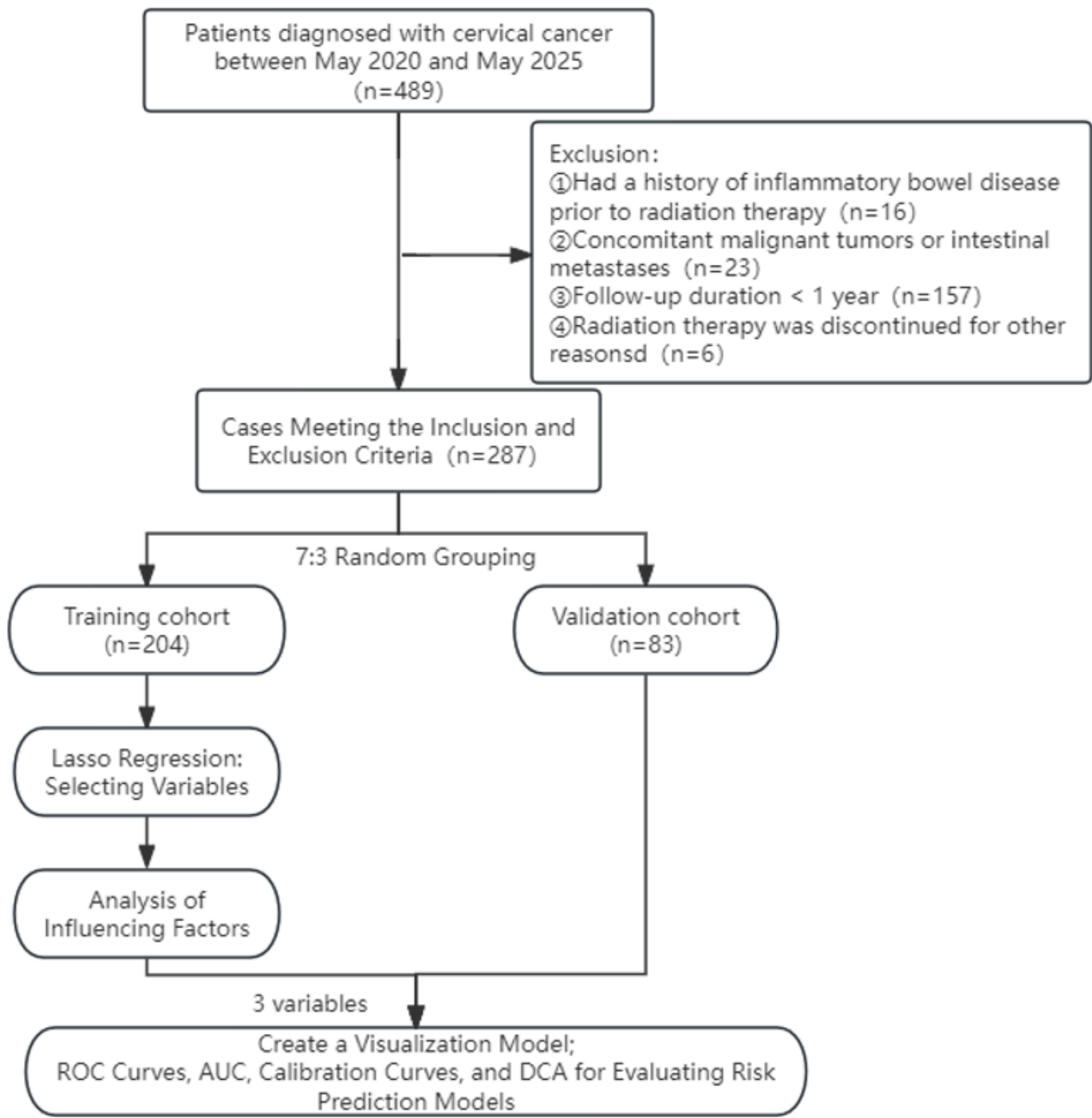


Figure 1

Legend not included with this version.

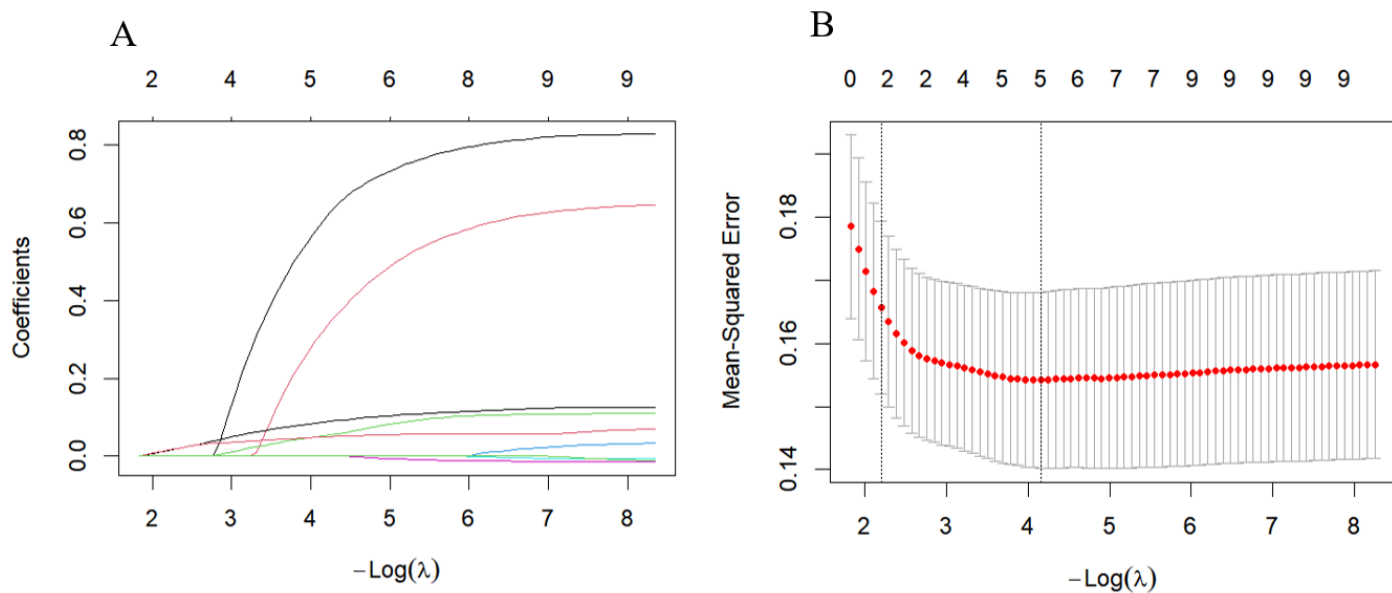


Figure 2

1: Variable feature selection based on Lasso regression (A: Coefficient path diagram; B: 10-fold cross-validation plot)

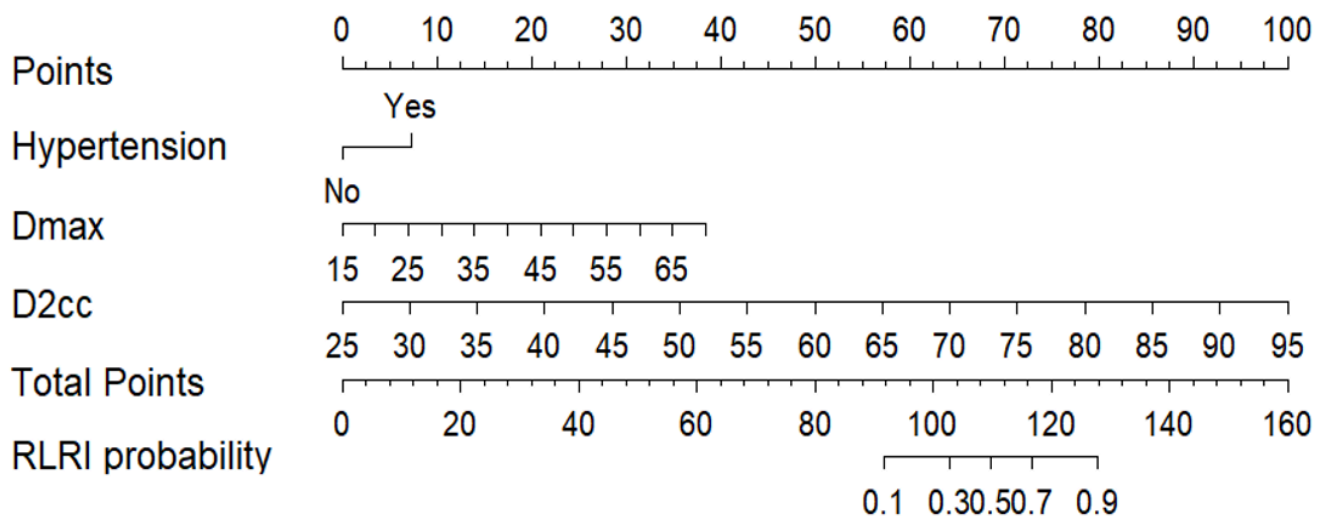


Figure 3

2: Visualization of a Model of Chronic Radiation-Induced Rectal Injury, Grade ≥ 2

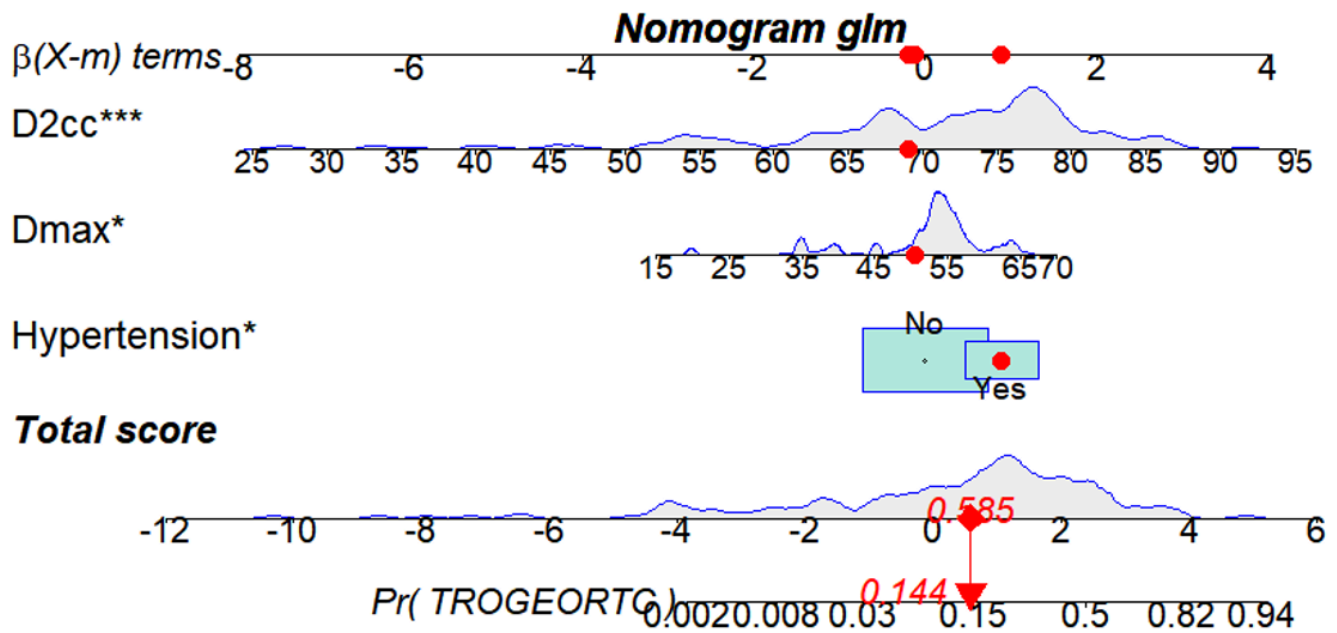


Figure 4

3: Visualization of the interactive contour plot model for RLRIof grade ≥ 2

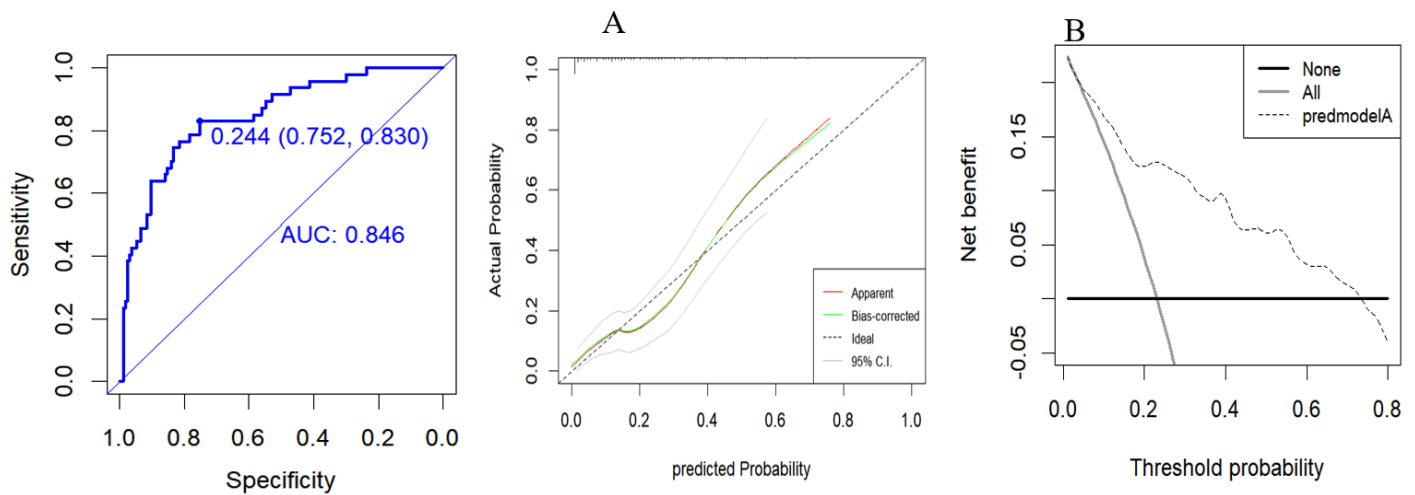


Figure 5

4: ROC curve (A), calibration curve (B), and DCA curve (C) for the training set

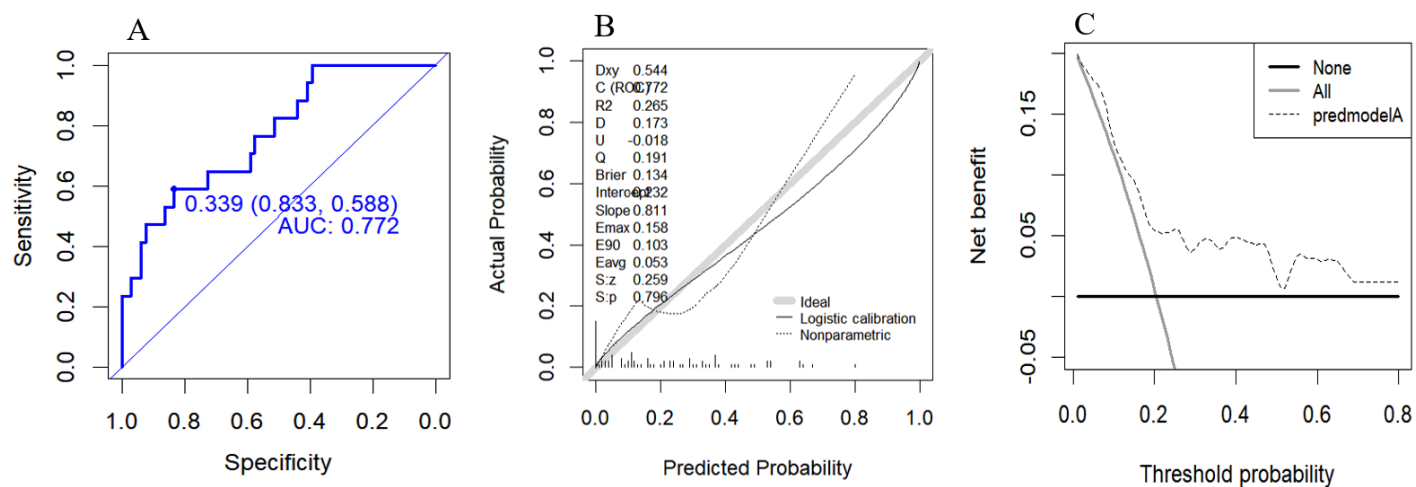


Figure 6

5: ROC curve (A), calibration curve (B), and DCA curve (C) for the validation set

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Additionalfile1.csv](#)