

Original Article

Efficacy of root canal treatment for chronic apical periodontitis: risk factor analysis and development of a nomogram for outcome prediction

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Abstract: Objectives: To evaluate the efficacy of root canal treatment in chronic apical periodontitis (CAP) and identify risk factors for poor prognosis and to develop a nomogram for personalized risk assessment. Methods: This retrospective study enrolled 149 CAP patients treated at the 901 Hospital of Joint Logistics Support Force of People Liberation Army from October 2022 to May 2024. Data on demographics, smoking, diabetes, Old Periapical Index (O-PAI), visual analogue scale (VAS), and root canal curvature were collected. Independent risk factors were identified using multivariate logistic regression, followed by nomogram construction. Model performance was assessed using the receiver operating characteristic (ROC) curve, while calibration curves and decision curve analysis (DCA) were used. Results: Root canal treatment significantly improved O-PAI scores in CAP patients [from 4.00 (3.00, 4.00) pre-treatment to 2.00 (1.00, 2.00)] and significantly reduced VAS pain scores by day 7 post-treatment [(from 2.00 (1.00, 2.00) to 1.00 (1.00, 2.00), $P < 0.001$]. Multivariate analysis identified smoking (OR = 4.81, $P = 0.004$), diabetes (OR = 4.30, $P = 0.006$), higher pre-treatment VAS scores (OR = 2.36, $P = 0.002$), and greater root canal curvature (OR = 1.27, $P < 0.001$) as independent risk factors for poor prognosis. The nomogram model achieved an area under the ROC curve (AUC) of 0.85 in the internal validation and 0.78 in the external cohort. Conclusions: Root canal treatment demonstrates significant efficacy in CAP. Smoking, diabetes, elevated pre-treatment VAS scores, and greater root canal curvature are independent predictors of poor prognosis. The nomogram provides a useful tool for personalized risk assessment and clinical decision-making.

Keywords: Chronic apical periodontitis, root canal treatment, prognosis, risk factor analysis

Introduction

Apical periodontitis (AP) is an inflammatory disease of the periapical tissues caused by pulp infection, often secondary to pulp necrosis or untreated pulpal disease. Bacterial invasion through the root canal system triggers local immune responses leading to bone resorption and chronic inflammation [1]. Clinically, AP is divided into acute and chronic forms. Chronic apical periodontitis (CAP), which results from unresolved acute episodes or subclinical infections, manifests as persistent periapical inflammation lasting months to years and significantly impairs oral function and quality of life [1-3]. Globally, CAP is prevalent in adults, particularly those with dental caries, a history of pulpal disease, or untreated root canal in-

fections. Epidemiologic data suggests an overall CAP prevalence of up to 52%, with regional variations: lower rates occur in economically developed regions due to regular dental care compared to resource-limited areas [3-5]. Although studies of CAP prevalence in Chinese populations are scarce, existing research on other oral diseases suggests a worrisome scenario [6, 7].

Root canal therapy, the standard non-surgical approach for CAP, effectively controls infection, reduces inflammation, and restores tooth function [3, 8, 9]. However, despite advances, challenges remain, including residual chronic inflammation, incomplete apical healing, recurrence, and treatment failure [3, 10]. Reported root canal success rates for AP range from

70.0% to 87.4% [8, 10, 11]. Previous studies have identified factors associated with treatment failure and poor prognosis, such as operator skill, patient age, crown-to-root ratio, diabetes, hypertension, smoking, and alcohol consumption [3, 10, 12, 13]. However, current evidence remains inconclusive regarding the precise risk factors that influence therapeutic outcomes, highlighting the need for further investigation.

This study aimed to evaluate the efficacy of root canal treatment in the treatment of CAP and to investigate risk factors for poor prognosis. Through a retrospective analysis of clinical data from CAP patients undergoing root canal treatment, we used multivariate regression to identify critical prognostic determinants. Furthermore, we constructed a clinical data-driven prediction model to optimize personalized treatment strategies. Our findings are expected to provide evidence-based guidance for individualized clinical management and novel insight into prognostic evaluation for CAP.

Materials and methods

Study design

This retrospective study included 149 patients with CAP treated at the Department of Stomatology, the 901 Hospital of Joint Logistics Support Force of People Liberation Army from October 2022 to May 2024. Inclusion criteria: fulfillment of clinical and radiographic diagnostic criteria for CAP (only the first affected tooth was included when multiple teeth were involved); fully developed apical foramen. Exclusion criteria: history of root canal treatment; severe systemic diseases; severe periodontal lesions; psychiatric disorders; non-restorable residual roots or crowns, or root fractures; grade II or higher furcation involvement, pulp pathology or alveolar trauma; pregnancy or lactation; incomplete clinical data; inability to cooperate with treatment. Consecutive sampling was employed: all patients who met the predefined inclusion and exclusion criteria during the study period were sequentially enrolled. This study was approved by the Ethics Committee of the 901 Hospital of Joint Logistics Support Force of People Liberation Army (NO: 202502001). Due to the retrospective nature of this study, the Ethics Committee granted a waiver of informed con-

sent. All patient data were anonymized prior to analysis to protect patient privacy.

Root canal treatment

After treatment initiation, the tooth structure was restored, and a temporary wall was placed. The affected tooth was isolated using a rubber dam. Following pulp chamber access, a #10 K-file was used to assess root canal patency. Root canal preparation was carried out with Mtwo rotary nickel-titanium files in conjunction with 17% ethylenediaminetetraacetic acid (EDTA) gel to remove the smear layer. During instrumentation, alternating irrigation with 3% sodium hypochlorite (NaOCl) and EDTA was performed. The working length was determined using an electronic apex locator combined with a diagnostic radiograph, and the master apical file was selected to be three sizes larger than the initial apical file (at least #30). After drying the root canal with paper points, calcium hydroxide paste was applied to cover the apical third, and the access cavity was sealed tightly with temporary restorative material. The patient was reviewed after 10 days. During the follow-up visit, the following criteria were assessed: absence of percussion pain, closure/significant reduction of sinus tracts, absence of exudate, and no foul odor within the root canal. Radiographs were taken to evaluate the peri-apical healing trend. If these conditions were met, the temporary material was removed, and root canal obturation was performed using the main gutta-percha cone combined with the warm vertical condensation technique and AH-Plus sealer. All procedures were carried out by the same senior dentist.

Treatment efficacy

The visual analogue scale (VAS) was used to assess pain scores at baseline and at follow-up time points [14]. The scoring criteria were as follows: 0 points (no pain); less than 3 points (mild pain); 4-6 points (moderate pain); 7-10 points (severe pain). The efficacy of root canal treatment was evaluated based on changes in the Old-Periapical Index (O-PAI) scores between pre-treatment and six months post-treatment. A favorable prognosis was defined as a reduction of ≥ 1 grade in the O-PAI score from baseline and a post-treatment score ≤ 2 . Conversely, an unfavorable prognosis was defined as

no improvement or an increase in the O-PAI score, or a post-treatment score ≥ 3 [14, 15].

Data collection

Data were collected on all patients, including age, sex, BMI, education level, smoking status, alcohol consumption, diabetes, hypertension, pre-treatment O-PAI, crown-to-root ratio, root canal curvature, anemia, and C-reactive protein (CRP) levels. These variables were analyzed to identify risk factors associated with poor prognosis. The six-month post-treatment O-PAI score was used as the outcome variable, with an O-PAI score ≥ 3 considered indicative of poor prognosis.

Model validation and interpretation

We first presented the internal validation results, demonstrating that the model exhibits strong discriminative ability, good calibration, and clinical utility in the original cohort. Next, we provided the Shapley Additive Explanations (SHAP) based interpretation, thereby explaining the contribution of each feature to the model's predictions. Finally, we presented the external validation results, confirming that the model maintains satisfactory performance in an independent cohort of 45 patients.

Statistical analysis

All statistical analyses were performed using SPSS version 27.0, with a two-sided significance level of $\alpha = 0.05$. Continuous data were tested for normality. Data conforming to a normal distribution were expressed as mean $\pm$ standard deviation (SD), and within-group comparisons were performed using paired t-tests. Non-normally distributed data were expressed as medians and interquartile ranges [M (P25, P75)], and within-group comparisons were made using the Wilcoxon signed-rank test. Categorical data were expressed as frequencies and percentages [n (%)], and comparisons were made using the chi-squared test (Fisher's exact test was used when the expected frequency was < 5). Potential risk factors were screened using univariate logistic regression with a significance level of $P < 0.05$ for entry into the multivariate logistic regression, to identify independent risk factors, with adjusted odds ratios (ORs) and 95% confidence intervals (95% CI) calculated. Based on the regres-

sion results, a nomogram model was constructed to predict outcome probabilities. Model performance was evaluated using receiver operating characteristic (ROC) curve analysis to assess discrimination (AUC), calibration curves to assess calibration accuracy, and decision curve analysis (DCA) to quantify net clinical benefit. Missing data were present in $< 5\%$ of continuous variables and were imputed using medians or means based on the distribution of each variable. Statistical significance was set at $P < 0.05$ for all tests.

Results

Baseline characteristics of patients

Patients were categorized into two groups based on their O-PAI scores at six months post-treatment: good prognosis (O-PAI < 3 , $n = 117$) and poor prognosis (O-PAI ≥ 3 , $n = 32$). Among the 32 patients classified as poor prognosis at 6 months, 9 (28.1%) showed radiographic improvement from baseline but had not yet achieved an O-PAI < 3 , suggesting that some may achieve complete healing with extended follow-up. As shown in **Table 1**, a total of 149 patients with CAP were included in this study, comprising 68.46% males and 31.54% females. The median age was 31 years, and the mean BMI was 21.44 ± 1.79 kg/m². Most patients had an educational level of high school or above (63.09%). The proportions of patients who smoked and drank alcohol were 48.32% and 46.98%, respectively. Additionally, the incidence of common conditions such as diabetes, hypertension, and anemia was 34.23%, 25.50%, and 32.89%, respectively. Dental measurements revealed that the mean crown-to-root ratio of the affected teeth was 0.75 ± 0.14 , with an average root canal curvature of $18.72^\circ \pm 4.83^\circ$. The median C-reactive protein (CRP) level was 2.0 mg/L.

O-PAI and VAS scores before and after treatment

Table 2 presents the pre- and post-treatment O-PAI and VAS scores. The median O-PAI score at admission was 4.00 (3.00-4.00), which significantly decreased to 2.00 (1.00-2.00) at six months post-treatment ($P < 0.001$). Similarly, the median VAS pain score before treatment was 2.00 (1.00-2.00). No significant improvement in VAS scores was observed on days 1

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Table 1. Characteristics of all patients

Variable	good prognosis (n = 117)	poor prognosis (n = 32)	t/ χ^2 /u	P
Sex [n (%)]			0.002	0.968
Male	80	22		
Female	37	10		
Age [M (P25, P75)]	28.0 (22.0, 41.0)	39.0 (26.0, 65.0)	2.412	0.016
BMI ($\bar{x} \pm s$)	21.31 $\pm$ 1.64	21.89 $\pm$ 2.22	1.644	0.102
Educational level [n (%)]			2.385	0.496
Primary and below	22	9		
Junior high school	30	6		
Senior high school	31	6		
College and above	34	11		
Smoking [n (%)]			6.810	0.009
No	67	10		
Yes	50	22		
Drinking [n (%)]			0.661	0.416
No	60	19		
Yes	57	13		
Diabetes [n (%)]			8.779	0.003
No	84	14		
Yes	33	18		
Hypertension [n (%)]			0.282	0.595
No	86	25		
Yes	31	7		
Anemia [n (%)]			0.419	0.518
No	77	23		
Yes	40	9		
Crown-to-root ratio ($\bar{x} \pm s$)	0.76 $\pm$ 0.14	0.73 $\pm$ 0.14	1.005	0.317
Root canal curvature ($\bar{x} \pm s$)	17.88 $\pm$ 4.60	21.82 $\pm$ 4.43	4.329	< 0.001
C-reactive protein ($\bar{x} \pm s$)	2.14 $\pm$ 1.47	2.13 $\pm$ 1.41	.051	0.960

BMI, Body Mass Index. Statistical symbols: t, χ^2 , and u represent the test statistics for t-test, chi-square test, and Mann-Whitney U test, respectively; P values < 0.05 were considered significant.

and 5 after treatment; however, a significant reduction was noted by day 7, with a median score of 1.00 (1.00-2.00) ($P < 0.001$).

Univariate Logistic regression analysis of poor prognosis in CAP patients following root canal treatment

Patients were categorized into two groups based on their O-PAI scores at six months post-treatment: good prognosis (O-PAI < 3) and poor prognosis (O-PAI $\geq$ 3). As shown in **Table 3**, univariate Logistic regression analysis revealed that older age (OR = 1.03, 95% CI: 1.01-1.05), smoking (OR = 2.95, 95% CI: 1.28-6.78), diabetes (OR = 3.27, 95% CI: 1.46-7.33),

higher pre-treatment O-PAI scores (OR = 1.87, 95% CI: 1.03-3.38), and higher pre-treatment VAS pain scores (OR = 2.42, 95% CI: 1.49-3.94) were significantly associated with an increased risk of poor prognosis ($P < 0.05$). Additionally, greater root canal curvature was also significantly associated with a higher risk of poor prognosis (OR = 1.20, 95% CI: 1.09-1.31, $P < 0.001$). Notably, higher education levels were identified as protective factors against poor prognosis, with middle school education (OR = 0.22, 95% CI: 0.06-0.78, $P < 0.05$) and high school education (OR = 0.12, 95% CI: 0.04-0.42, $P < 0.001$) significantly reducing the risk.

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Table 2. O-PAI and VAS for all patients

Variable	good prognosis (n = 117)	poor prognosis (n = 32)	u	P
O-PAI [M (P25, P75)]				
Before treatment	4.00 (3.00, 4.00)	4.00 (4.00, 5.00)	2.101	0.036
6 months after treatment	1.00 (1.00, 2.00)***	3.00 (3.00, 3.00)***	9.272	< 0.001
VAS [M (P25, P75)]				
Before treatment	1.00 (1.00, 2.00)	2.00 (1.00, 3.00)	3.676	< 0.001
1 day after treatment	2.00 (1.00, 2.00)	2.00 (1.00, 2.00)	0.091	0.927
5 days after treatment	2.00 (1.00, 2.00)	1.00 (1.00, 2.00)	0.020	0.984
7 days after treatment	1.00 (1.00, 2.00)***	1.00 (1.00, 2.00)***	0.178	0.859

O-PAI, Old Periapical Index; VAS, visual analogue scale. $P < 0.001$ compared to Before treatment. Statistical symbols: u represents the test statistic for the Mann-Whitney U test; P values < 0.05 were considered significant. ***: $P < 0.001$.

Table 3. Univariate Logistic regression analysis of poor prognosis in patients with CAP

Variable	β	S.E	Z	P	OR (95% CI)
Sex					
Male					Ref
Female	-0.02	0.43	-0.04	0.968	0.98 (0.42-2.28)
Age	0.02	0.01	1.71	0.087	1.02 (1.00-1.04)
BMI	0.18	0.11	1.62	0.105	1.20 (0.96-1.49)
Educational level					
Primary and below					Ref
Junior high school	-0.72	0.60	-1.20	0.231	0.49 (0.15-1.58)
Senior high school	-0.75	0.60	-1.26	0.209	0.47 (0.15-1.52)
College and above	-0.23	0.53	-0.45	0.656	0.79 (0.28-2.22)
Smoking					
No					Ref
Yes	1.08	0.42	2.55	0.011	2.95 (1.28-6.78)
Drinking					
No					Ref
Yes	-0.33	0.40	-0.81	0.417	0.72 (0.33-1.59)
Diabetes					
No					Ref
Yes	1.19	0.41	2.88	0.004	3.27 (1.46-7.33)
Hypertension					
No					Ref
Yes	-0.25	0.48	-0.53	0.596	0.78 (0.31-1.98)
Anemia					
No					Ref
Yes	-0.28	0.44	-0.65	0.518	0.75 (0.32-1.78)
O-PAI before treatment	0.62	0.30	2.06	0.039	1.87 (1.03-3.38)
VAS before treatment	0.89	0.25	3.57	< 0.001	2.42 (1.49-3.94)
Crown-to-root ratio	-1.46	1.45	-1.01	0.315	0.23 (0.01-3.99)
Root canal curvature	0.18	0.05	3.87	< 0.001	1.20 (1.09-1.31)
C-reactive protein	-0.04	0.14	-0.27	0.786	0.96 (0.73-1.26)

CAP, chronic apical periodontitis; BMI, Body Mass Index; O-PAI, Old Periapical Index; VAS, visual analogue scale. Statistical symbols: β , regression coefficient; S.E., standard error; Z, Wald test statistic; OR, odds ratio; 95% CI, 95% confidence interval; P values < 0.05 were considered significant.

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Table 4. Multivariate logistic regression analysis of poor prognosis in patients with CAP

Variable	β	S.E	Z	P	OR (95% CI)
Smoking					
No					Ref
Yes	1.38	0.57	2.44	0.015	3.99 (1.31-12.11)
Diabetes					
No					Ref
Yes	1.35	0.54	2.48	0.013	3.86 (1.33-11.20)
VAS before treatment	0.90	0.29	3.11	0.002	2.47 (1.40-4.36)
Root canal curvature	0.24	0.06	4.11	< 0.001	1.28 (1.14-1.44)

CAP, chronic apical periodontitis; VAS, visual analogue scale. Statistical symbols: β , regression coefficient; S.E., standard error; Z, Wald test statistic; OR, odds ratio; 95% CI, 95% confidence interval; *P* values < 0.05 were considered significant.

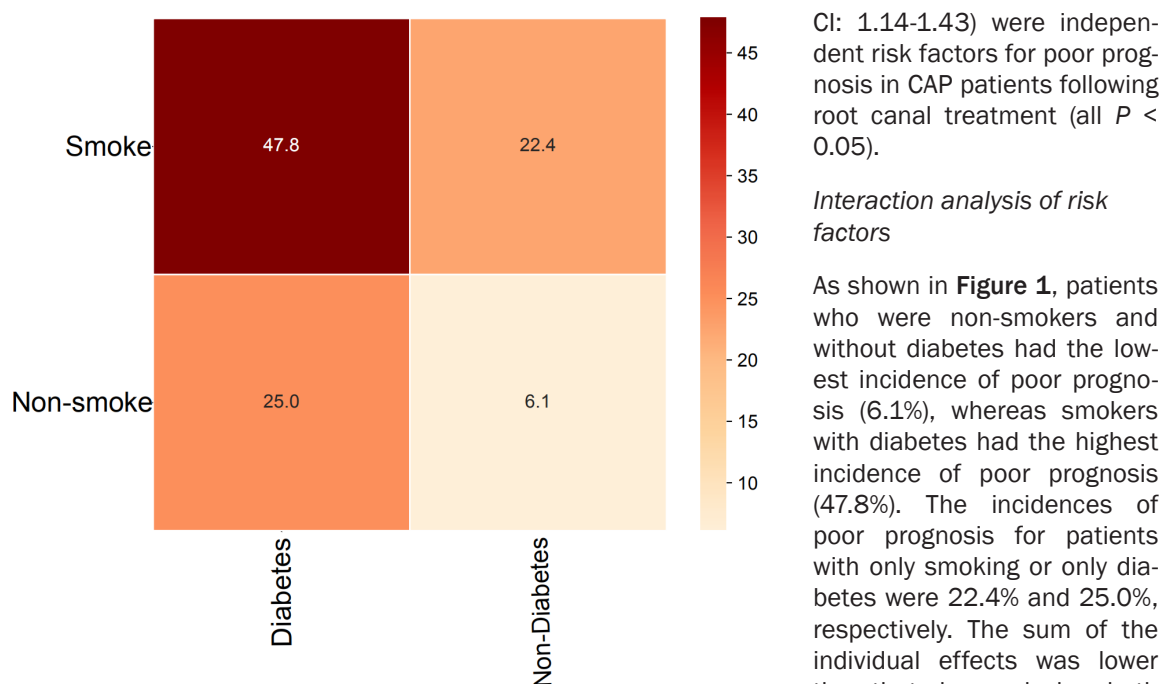


Figure 1. Interaction between smoking and diabetes on poor prognosis after root canal treatment in CAP patients. Notes: CAP, chronic apical periodontitis. Percentages represent the proportion of poor prognosis within each subgroup.

Multivariate logistic regression analysis of poor prognosis in CAP patients following root canal treatment

Variables with *P* < 0.05 in the univariate analysis were entered into the multivariate Logistic regression model. As shown in **Table 4**, the results indicated that smoking (OR = 4.81, 95% CI: 1.63-14.16), diabetes (OR = 4.30, 95% CI: 1.53-12.11), higher pre-treatment VAS pain scores (OR = 2.36, 95% CI: 1.36-4.09), and greater root canal curvature (OR = 1.27, 95%

CI: 1.14-1.43) were independent risk factors for poor prognosis in CAP patients following root canal treatment (all *P* < 0.05).

Interaction analysis of risk factors

As shown in **Figure 1**, patients who were non-smokers and without diabetes had the lowest incidence of poor prognosis (6.1%), whereas smokers with diabetes had the highest incidence of poor prognosis (47.8%). The incidences of poor prognosis for patients with only smoking or only diabetes were 22.4% and 25.0%, respectively. The sum of the individual effects was lower than that observed when both factors were present, suggesting a synergistic effect.

Construction of the nomogram prediction model

As shown in **Figure 2**, a nomogram predictive model was constructed based on the multivariate Logistic regression analysis, incorporating the four identified independent risk factors: smoking, diabetes, baseline VAS pain score, and root canal curvature. The model assigns a score to each predictive factor according to its contribution to the outcome variable, and the total score is used to predict the risk of poor prognosis following root canal treatment in CAP patients. This tool provided a visual and quantitative approach to estimate the likeli-

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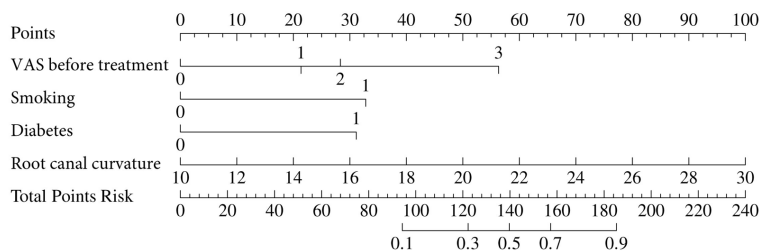


Figure 2. Nomogram predictive modeling. Notes: VAS, visual analogue scale. Smoking: 0-No, 1-Yes. Diabetes: 0-No, 1-Yes. Scoring instructions: each predictor is assigned a point value on the top scale; the sum of all points corresponds to the predicted probability of poor prognosis on the bottom scale.

hood of adverse outcomes, offering valuable support for individualized interventions in clinically high-risk patients.

Validation of the nomogram prediction model

The performance of the nomogram model was validated using several metrics. First, the AUC was calculated to quantify the model's ability to distinguish between patients with good and poor prognosis. As shown in **Figure 3A**, the AUC was 0.85, indicating good discriminatory power. Next, calibration of the model was assessed by plotting a calibration curve and performing the Hosmer-Lemeshow goodness-of-fit test. As illustrated in **Figure 3B**, the calibration curve demonstrated that the predicted probabilities closely aligned with the observed outcomes, suggesting good model calibration. Finally, DCA was performed to evaluate the model's clinical utility by quantifying the Net Benefit across different risk thresholds. As shown in **Figure 3C**, the model provided a higher net benefit compared to the "All" and "None" strategies within a certain range of thresholds.

Model interpretation based on SHAP

The SHAP method was employed to interpret the predictive outcomes of the model (**Figure 4**). Based on the analysis of mean absolute SHAP values, root canal curvature was identified as the top-ranked risk factor (**Figure 4A**). **Figure 4B** illustrates the directional impact of each feature on the model prediction. The distribution characteristics of SHAP values indicate that smoking, diabetes, and higher baseline VAS scores were all associated with an elevated risk of poor prognosis.

External validation of the predictive model

Among the external validation cohort, 11 patients had a poor prognosis and 34 had good prognosis. We further validated the prediction model in the independent external cohort. The results revealed an AUC of 0.78 (95% CI: 0.60-0.96) for the external cohort, which was slightly lower than 0.85 for the training set (95% CI: 0.77-

0.93), but still indicated a satisfactory discriminative ability (**Figure 5A**). The calibration curve showed a good agreement between predicted and observed risks across all risk quantiles (Hosmer-Lemeshow test, $P = 0.382$) (**Figure 5B**). Additionally, decision curve analysis confirmed the model's clinical utility, with significant net benefits observed when the probability threshold was set between 0.18 and 0.82 (**Figure 5C**).

Discussion

Chronic apical periodontitis (CAP) is a common inflammatory disease of the periapical tissues caused by pulp infection with a high prevalence worldwide, especially in adults [1]. Root canal treatment, as the primary nonsurgical therapy for CAP, has been shown to be highly effective in reducing inflammation and restoring tooth function [8, 16]. This study demonstrated that O-PAI scores were significantly reduced after root canal treatment. Furthermore, the VAS scores on the seventh day after treatment were significantly improved compared to the pre-treatment scores. In univariate logistic regression analysis, this study found that older age, smoking, diabetes, higher pretreatment VAS scores, and greater root canal curvature significantly increased the risk of poor prognosis, while higher education level was identified as a protective factor. Further multivariate Logistic regression analysis confirmed that smoking, diabetes, higher pretreatment VAS scores, and greater root canal curvature were independent risk factors for poor prognosis. These findings provide a basis for optimizing individualized treatment strategies for CAP patients.

Some studies suggest that men are slightly more likely to develop CAP, while others have

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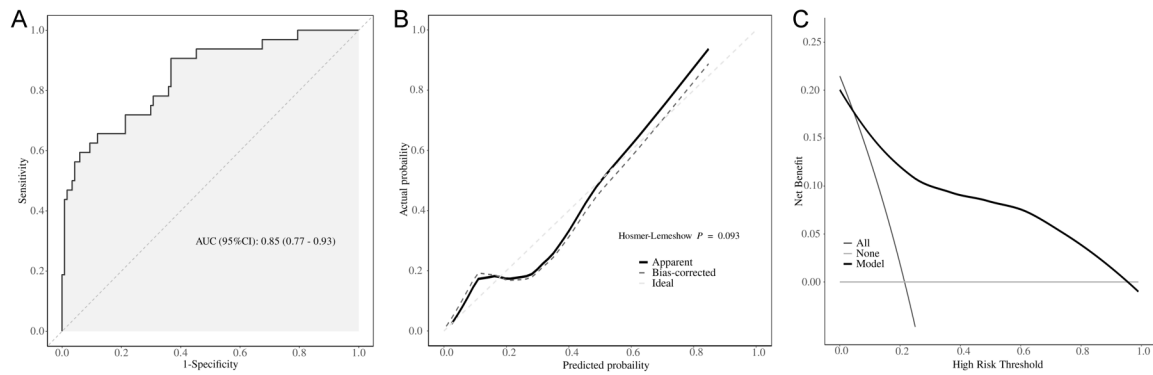


Figure 3. Validation of nomogram prediction model. A. ROC curve. B. Calibration Curve and Hosmer-Lemeshow test. C. DCA curve. Notes: ROC, Receiver Operating Characteristic; AUC, Area Under the Curve; DCA, Decision Curve Analysis.

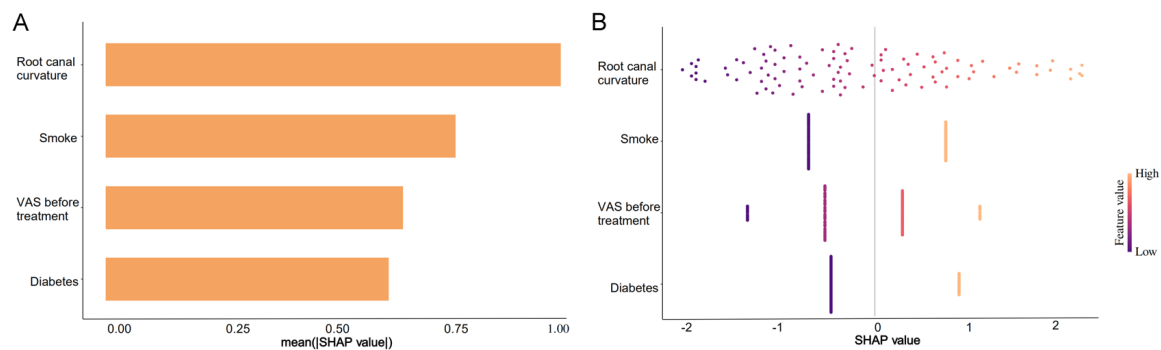


Figure 4. Model interpretation using SHAP. A. The importance of each feature as determined by mean absolute SHAP values. B. The impact of each feature on the model output. Each dot represents an individual patient; its horizontal position corresponds to the SHAP value (indicating the feature's impact on the prediction), and the color corresponds to the original feature value (orange for high, purple for low). Notes: VAS, visual analogue scale; SHAP, Shapley Additive Explanations. Statistical symbols: SHAP values represent the contribution of each feature to the predicted outcome; each dot represents an individual patient; horizontal position, SHAP value (positive values indicate increased risk); color, original feature value (orange = high, purple = low).

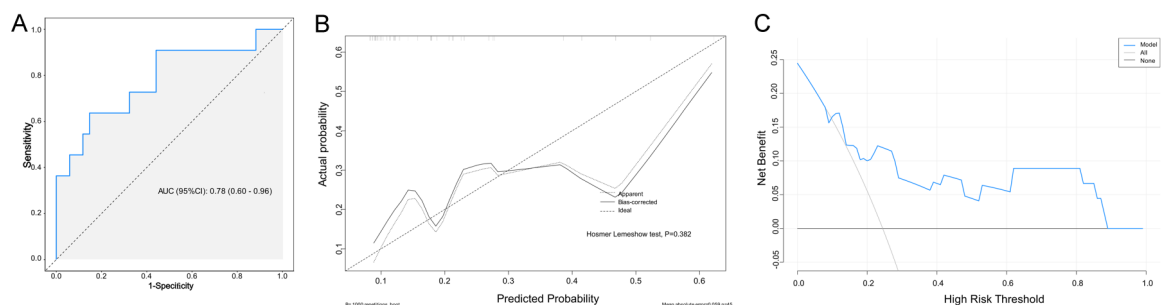


Figure 5. External validation of the predictive model. A. The ROC curve evaluating discrimination. B. The calibration plots present the agreement between predicted and observed outcomes. C. DCA depicts the net clinical benefit of the model. Notes: ROC, Receiver Operating Characteristic; AUC, Area Under the Curve; DCA, Decision Curve Analysis.

found no significant gender differences [17, 18]. Overall, gender has a minimal effect on the incidence of CAP. Among the patients included in this study, we observed a higher

number of male patients, but no significant effect of gender on the prognosis of CAP after root canal treatment was found. The incidence of oral diseases, including CAP, generally rises

with age, especially in adults over 40 years. However, recent studies have also reported a considerable proportion of cases in younger populations [19, 20]. In this study, we found that the median age of CAP patients was 31 years. Further univariate logistic regression analysis indicated that older age may be associated with poor prognosis of CAP after root canal treatment, although it was not identified as an independent risk factor.

Smoking is associated with the onset and progression of oral diseases [13]. Research by Paljevic et al. has shown that smoking significantly increases the risk of persistent AP and reduces the healing rate of periapical inflammation [21]. Studies suggest that smoking may affect treatment outcomes by suppressing immune function, delaying tissue healing, and exacerbating inflammation. In addition, smokers tend to have a higher bacterial load in periapical infections, which may be related to the immunosuppressive effects of nicotine [22-24]. In this study, we found that smoking was an independent risk factor for poor prognosis in CAP patients after root canal treatment (OR: 4.81, $P = 0.004$), which is consistent with existing research. Therefore, smoking cessation is not only beneficial for overall health, but also an important measure to improve the efficacy of root canal treatment in CAP patients.

In addition to promoting the overexpression of inflammatory factors, a hyperglycemic environment may alter the composition of the microbiota within root canals, adding to the complexity of endodontic management. Diabetes affects the onset and progression of oral disease through multiple mechanisms, including impaired vascular function, reduced local immune responses, and delayed tissue repair [25]. Early studies have shown that the prevalence of periodontal disease is higher in diabetic patients than in the general population [26]. A recent study showed that diabetes may significantly increase the risk of developing AP after endodontic treatment [27]. Similarly, we found that diabetes significantly increased the risk of poor prognosis in AP patients (OR: 4.30, $P = 0.006$). This study highlights that strict glycemic control, and regular postoperative follow-up may contribute to the success of root canal treatment in diabetic patients.

Although CAP typically does not cause severe pain to patients (unlike AP), many still experience significant discomfort [14]. In this study, we found that a higher pre-treatment VAS score was another important independent predictor of poor prognosis in CAP patients undergoing root canal treatment (OR: 2.36, $P = 0.002$). Elevated VAS scores often indicate more severe periapical infection and more extensive tissue damage, which may limit the effectiveness of root canal therapy [28]. For these patients, enhanced cleaning and disinfection strategies should be implemented during treatment, and appropriate anti-inflammatory and analgesic measures should be provided post-operatively to alleviate symptoms and promote healing.

The complex anatomy of root canals presents challenges to thorough cleaning and shaping, increasing the likelihood of bacterial persistence [29]. The introduction of modern nickel-titanium instruments has alleviated this problem to some extent; however, for patients with highly curved root canals, preoperative evaluation and intraoperative microscopic techniques remain critical [30]. In this study, we found that patients with greater root canal curvature had a significantly increased risk of poor prognosis (OR: 1.27, $P < 0.001$).

Notably, this study found that patients with higher levels of education had a better prognosis by univariate analysis. Higher levels of education may increase patients' awareness of the importance of postoperative care and follow-up, thereby improving adherence and health literacy, both of which contribute to better disease outcomes. Previously, a study from Saudi Arabia indicated that education level and occupational status were important determinants of oral health self-efficacy scores [31]. Consistent with previous research, our findings suggest that efforts should be made to strengthen health education and postoperative management for patients with lower educational levels.

Several limitations of this study should be acknowledged. First, the retrospective single-center design carries inherent selection bias. Although consecutive enrollment was used, unmeasured confounding remains possible. Moreover, the single-center nature limits generalizability to other settings. In addition, the

sample size ($n = 149$) is modest, especially for multivariate modeling, which may limit power to detect some associations. The external validation cohort was small ($n = 45$, 11 events), leading to wide confidence intervals and reduced precision. While the model still demonstrated acceptable discriminative ability ($AUC = 0.78$) and satisfactory calibration (Hosmer-Lemeshow test $P = 0.382$) in this independent cohort, these results should be interpreted as preliminary evidence supporting the model's generalizability rather than definitive confirmation. Future multi-center studies with larger sample sizes are warranted to further validate and refine our nomogram across different clinical settings and populations. The incidence of CAP and treatment outcomes may be influenced by genetic factors, such as variations in genes involved in immune response, which were not evaluated in this study. In addition, the microbial composition of root canal infections may influence the success rate of root canal treatment, but we did not perform microbiological analysis. Finally, the follow-up period was limited to 6 months. Although the European Society of Endodontology (ESE) guidelines recommend a minimum follow-up of 1 year for definitive outcome assessment, our 6-month endpoint serves as early prognostic indicators. Future studies with extended follow-up periods (≥ 1 year) are warranted to validate the long-term predictive value of our nomogram model. Because of the 6-month follow-up and the binary classification of O-PAI (≥ 3 vs. < 3) may not fully capture the dynamic healing process, our findings should be interpreted as early prognostic indicators, and longer-term studies are warranted to confirm the final outcomes.

In conclusion, root canal therapy is effective for CAP. Independent risk factors for poor prognosis include smoking, diabetes, higher baseline VAS score, and greater root canal curvature. The nomogram provides a valuable tool for personalized risk assessment. This research may contribute to the optimization of management strategies and technological advances in the future, further improving the success rate of root canal treatment and achieving better clinical outcomes for CAP patients.

Disclosure of conflict of interest

None.

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