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Predictive Value of Preoperative Radiographic Indices and Demographic Characteristics for Mandibular Third Molar Extraction Difficulty: A Retrospective Cohort Study

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AIM: This study aimed to investigate the predictive value of preoperative radiographic indices, demographic characteristics, and psychological factors for mandibular third molar extraction difficulty, to develop a nomogram, and to interpret feature contributions using SHapley Additive exPlanations (SHAP) analysis.
METHODS: In this retrospective cohort study of 250 patients, demographic characteristics, including age, sex, and body mass index (BMI), together with radiographic indices such as root morphology and psychological factors assessed using the Modified Dental Anxiety Scale (MDAS), were analyzed in relation to surgical difficulty, defined as operative time exceeding 45 minutes. Multivariate logistic regression was used to construct a nomogram, which was validated through receiver operating characteristic (ROC) curves and decision curve analysis (DCA). Feature importance was explored using SHAP analysis, and the association between operative time and perioperative outcomes was assessed.
RESULTS: Multivariate logistic regression identified age, root morphology, Winter's angulation, and preoperative dental anxiety (MDAS score) as key predictors of high surgical difficulty ($p < 0.05$). The resulting nomogram demonstrated excellent discrimination, with an area under the curve (AUC) of 0.91. SHAP analysis illustrated that age and Winter's angulation contribute more to the model's predictions, followed by root morphology. Longer operative time was independently associated with a higher risk of perioperative complications (odds ratio = 1.03, $p < 0.05$) and showed a positive correlation with pain intensity on postoperative day 1 (Spearman's $\rho = 0.712$, $p < 0.001$).
CONCLUSIONS: Bulbous or curved root morphology, advanced age, high dental anxiety, Winter's angulation, and male sex were associated with the difficulty of mandibular third molar extraction. The developed nomogram serves as a precise, clinically interpretable tool for preoperative risk stratification. Integrating psychological evaluation with anatomical assessment facilitates a holistic approach to surgical planning.

Keywords: mandibular third molar; extraction difficulty; preoperative radiographic assessment; root morphology; demographic characteristics; operative time

Introduction

Impaction of the mandibular third molar (MM3) represents one of the most prevalent developmental anomalies of the human jaw, making its extraction a fundamental procedure in oral and maxillofacial surgery [1]. Although the advent of minimally invasive techniques, such as piezoelectric and ultrasonic surgery, has mitigated surgical trauma, the incidence of postoperative complications—ranging from persistent pain and swelling to dry socket and inferior alveolar nerve injury—retains significant heterogeneity (4%–26%) across cases [2,3]. Thus, being able to accurately assess preoperative difficulty is necessary not only for resource allocation but also for the formulation of precise surgical protocols to circumvent iatrogenic injury [4].

Currently, the stratification of the widely used Winter's classification and Pell & Gregory (P&G) system is primarily contingent on the macroscopic spatial relationship of the impacted tooth relative to the second molar and the mandibular ramus. However, accumulating evidence suggests that these two-dimensional, macroscopic classifications possess inherent limitations in individual case prediction [5–7]. A critical deficit is their neglect of "micro-anatomic features"—specifically root morphology (e.g., curvature, furcation, and hypercementosis/bulbous roots)—which exert a decisive influence on surgical mechanics [8]. Complex root configurations, particularly the undercuts formed by bulbous roots, often necessitate extensive bone removal or intricate root sectioning, thereby exponentially increasing extraction resistance and surgical complexity [9,10].

Furthermore, surgery is not solely an anatomical challenge but also a test of the patient's psychophysiological reserve

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[11]. In China, the prevalence of dental anxiety among adults is reported to be as high as 35.39% [12]. Anxious states can trigger sympathetic nervous system activation, resulting in elevated intraoperative blood pressure, increased muscle tonus, and a lower pain threshold, all of which indirectly compound surgical complexity [13,14]. Although clinical experience suggests that highly anxious patients can be "harder to manage", quantitative models integrating psychological metrics with anatomical indices remain scarce [15,16]. The Modified Dental Anxiety Scale (MDAS) is a dental anxiety assessment tool tailored for adults, with good internal consistency, test-retest reliability, and cross-cultural validity, and is widely used in clinical practice and research [17,18]. However, although the validity of the MDAS has been confirmed, its potential association with surgical difficulty has not been fully investigated—a research gap that we intended to address in this study. To enhance clinical interpretability of statistical models, SHapley Additive exPlanations (SHAP), a game-theoretic post-hoc explanation tool, was utilized in this investigation to quantify the marginal contribution of each feature, for the purpose of clarifying the model's decision logic [19,20].

Therefore, this study aims to: (1) evaluate the predictive value of multiple factors, including root morphology, preoperative anxiety, anatomical parameters, and patient and surgeon characteristics on surgical difficulty using multivariate logistic regression; (2) construct a nomogram and utilize SHAP to intuitively parse feature weights; and (3) validate the association between operative time and perioperative outcomes (complications and pain).

Methods

Study Design and Participants

This retrospective cohort study was conducted in strict adherence to the ethical principles of the Declaration of Helsinki and the STROBE reporting guidelines. This retrospective study was approved by the Ethics Committee of The First People's Hospital of Yongkang (Yongkang First People's Hospital) (Approval No: EC2025-LW-041-01(K)). Participants were selected from consecutive patients undergoing MM3 extraction at the Department of Stomatology of The First People's Hospital of Yongkang between January 2021 and January 2024.

To ensure consistency in assessment, inclusion criteria included the following: (1) age $\geq$18 years; (2) high-quality orthopantomogram (OPG) conducted within one week preoperatively; (3) surgery performed under local anesthesia; and (4) availability of complete electronic medical records, including surgical notes and preoperative MDAS scores. Patients with pathological changes (cysts or tumors), systemic diseases classified as American Society of Anesthesiologists (ASA) Physical Status >II, and cases converted to general anesthesia due to poor intraoperative cooperation were excluded from this study. Ultimately, 250 valid samples were included in the analysis.

Data Collection

Predictive variables were categorized into three dimensions:

(1) Demographic and psychological characteristics: age (years), sex (male/female), body mass index (BMI, kg/m^2), and preoperative MDAS score (range from 5 to 25, with higher scores indicating greater dental anxiety).

(2) Clinical indicators: preoperative maximum mouth opening (mm), pericoronitis status (acute/chronic/none).

(3) Operator-related factor: surgeon level (specialist/resident).

(4) Radiographic classification: impacted angulation was determined via Winter's classification (mesioangular, horizontal, vertical, distoangular). Impaction depth was assessed using the P&G system (level A, B, C) alongside ramus relationship (class I, II, III). According to Lambade *et al*. [21] and Jayasuriy *et al*. [8], root morphology was stratified into four categories: conical/fused, divergent, curved, and bulbous. Among them, conical/fused roots are characterized by a single conical root or multiple fused roots with a smooth and conical outline; divergent roots are characterized by two or more roots separating at the root tip with an increased interroot angle; curved roots are characterized by one or more roots exhibiting obvious apical curvature or hook-shaped deviation; and bulbous roots refer to root tip enlargement, featuring a rounded or enlarged root tip outline, which may form an undercut in the alveolar socket. Additionally, periodontal ligament (PDL) width (normal: clear radiolucency; obscure: blurred/absent, suggesting ankylosis) and inferior alveolar nerve (IAN) contact risk (high/low) were recorded.

Outcome variables were defined at three levels. The primary outcome was operative time (in minutes)—defined as the interval from mucosal incision to suture completion—which was used as an indicator of surgical difficulty. The application of this time-based classification scheme in this study was justified by its common usage in previous studies as a surrogate marker of the technical complexity of mandibular third molar extractions and as a parameter for stratifying difficulty [21,22]. Operative time was categorized into four levels: simple ($\leq$15 minutes), moderate (15 minutes<operative time$\leq$30 minutes), difficult (30 minutes<operative time$\leq$45 minutes), and very difficult (>45 minutes).

Secondary outcomes included perioperative complications (dry socket, nerve exposure, hemorrhage, root fracture) and pain intensity on postoperative day 1, measured using Visual Analogue Scale (VAS, 0–10).

Radiographic parameters were independently evaluated by two senior oral surgeons. Discrepancies were resolved by a third senior surgeon.

All study variables were perioperative indicators routinely documented in standard clinical and operative records and systematically recorded in the electronic medical record system. Therefore, no missing values were present for the analyzed variables among the included patients. Accordingly, a complete-case analysis was performed, and no imputation was required.

Sample Size Justification

To ensure the robustness of the multivariate logistic regression and prevent overfitting, the "events per variable (EPV)" principle was applied [23]. For the outcome variable "surgical difficulty", the cohort of 250 patients was divided into two groups: "high-difficulty" (difficult + very difficult, n = 157) and "low-difficulty" (easy + moderate, n = 93). Using the smaller sample size group (n = 93) as a reference, the EPV was calculated based on the effective degrees of freedom derived from variable coding. Age and MDAS score were continuous variables (1 degree of freedom), sex was a binary variable (1 degree of freedom), and Winter's angulation and root morphology were categorical variables (3 degrees of freedom), resulting in a total of 9 degrees of freedom. Therefore, the calculated EPV was 93/9 $\approx$ 10.33, meeting the recommended minimum requirement of EPV $\geq$10.

Statistical Analysis

Descriptive and Baseline Analyses

Statistical analyses were performed using R software (version 4.3.0; R Core Team, R Foundation for Statistical Computing, Vienna, Austria). The normality of continuous variables was assessed using the Shapiro–Wilk test. Since the data were verified as non-normally distributed, they were described using medians and interquartile ranges (IQR) and compared using the Kruskal–Wallis H test. Categorical variables were analyzed using the Chi-square test or Fisher's exact test, as appropriate. Fisher's exact test was used when the expected cell counts were insufficient for the Chi-square test.

Predictive Modeling and Variable Selection

Subsequently, in predictive modeling, surgical difficulty was divided into low-difficulty (easy + moderate) and high-difficulty (difficult + very difficult) categories, and these were treated as the dependent variable in logistic regression analysis.

Variable selection was performed using a two-step method: The first step involves integrating variables with $p < 0.05$ in the univariate logistic regression into the preliminary multivariate regression. In the second step, the predictors with $p < 0.05$ in the preliminary multivariate regression were selected. Before constructing the final multivariate model, multicollinearity among candidate predictors was assessed using variance inflation factors (VIFs) or generalized variance inflation factors (GVIFs), as appropriate, and a value of <5 was considered acceptable. Finally, these variables are included in the final multivariate logistic regression model to construct a nomogram.

Model Performance Evaluation and Interpretability

Model performance was evaluated using the area under the curve (AUC) and calibration (bootstrap method, 1000 resampling cycles). Clinical utility was assessed using decision curve analysis (DCA). SHAP values were calculated to visualize feature importance.

Analyses of Operative Time and Perioperative Outcomes

In the secondary analysis, the operation time was treated as a continuous variable to examine its association with perioperative outcomes, rather than being used as a surrogate indicator of surgical difficulty. Three sequential logistic regression models were fitted for perioperative complications. Model 1 was unadjusted. Model 2 adjusted for core demographic covariates (sex, age, and BMI). Model 3 was specified as an exploratory sensitivity model that additionally adjusted for preoperative anatomical and surgeon-related variables, including preoperative pericoronitis, Winter's angulation, P&G depth, P&G ramus relationship, root morphology, PDL width, IAN risk, surgeon level, mouth opening, and MDAS score. Given the limited number of complication events relative to the number of covariates, the estimates from Model 3 were interpreted cautiously as exploratory rather than confirmatory. The association between operative time and postoperative day 1 VAS pain scores was evaluated using Spearman's rank correlation. A two-sided $p < 0.05$ was considered statistically significant.

Results

Baseline Characteristics

The study included 250 patients with a balanced sex distribution (male: 48.0%; female: 52.0%). The median age was 28.00 years (IQR: 24.00–35.00). Radiographically, mesioangular impaction (36.4%) and P&G level B (46.0%) were predominant. Regarding root morphology, divergent roots were most common (32.8%), followed by conical/fused (26.0%) and curved roots (25.2%), with bulbous roots accounting for 16.0% (Table 1).

Stratification of Difficulty

Surgery-related indicators are summarized in Table 2. The median operative time was 36.85 minutes (IQR: 20.70–59.30). According to the operative time, 157 patients (62.8%) were classified into the high-difficulty group (including both 'difficult' and 'very difficult'), of which up to 38.8% of the patients belonged to the 'very difficult' level, accounting for the highest proportion. The median VAS pain score on the first day after surgery was 4.00 (IQR: 2.00–6.00). The total incidence of perioperative complications was 22.0%, encompassing hemorrhage

Table 1. Baseline demographic, clinical, and radiographic characteristics of the study population.

Variables	Total (n = 250)
Age (years), M (Q_1, Q_3)	28.00 (24.00, 35.00)
BMI (kg/m^2), M (Q_1, Q_3)	23.90 (21.80, 26.00)
Mouth opening (mm), M (Q_1, Q_3)	44.00 (40.00, 47.00)
MDAS anxiety score, M (Q_1, Q_3)	11.00 (9.00, 13.00)
Sex, *n* (%)	
Female	130 (52.00)
Male	120 (48.00)
Preoperative pericoronitis, *n* (%)	
Acute	25 (10.00)
Chronic	53 (21.20)
None	172 (68.80)
Winter's angulation, *n* (%)	
Distoangular	43 (17.20)
Horizontal	65 (26.00)
Mesioangular	91 (36.40)
Vertical	51 (20.40)
P&G level, *n* (%)	
Level A	63 (25.20)
Level B	115 (46.00)
Level C	72 (28.80)
P&G ramus, *n* (%)	
Class I	112 (44.80)
Class II	93 (37.20)
Class III	45 (18.00)
Root morphology, *n* (%)	
Bulbous	40 (16.00)
Conical/Fused	65 (26.00)
Curved	63 (25.20)
Divergent	82 (32.80)
PDL width, *n* (%)	
Normal	183 (73.20)
Obscure	67 (26.80)
IAN risk, *n* (%)	
High risk	50 (20.00)
Low risk	200 (80.00)
Surgeon level, *n* (%)	
Resident	24 (9.60)
Specialist	226 (90.40)

Notes: Values are presented as numbers (percentages) for categorical variables and medians (interquartile ranges [IQRs]) for continuous variables. Abbreviations: BMI, body mass index; IAN, inferior alveolar nerve; MDAS, Modified Dental Anxiety Scale; P&G, Pell & Gregory; PDL, periodontal ligament; M, Median; Q_1, 1st Quartile; Q_3, 3rd Quartile.

(6.0%), nerve exposure (5.6%), dry socket (5.2%), and root fracture (5.2%).

Table 3 presents a comparison of demographic, clinical, and radiographic variables across the four operative time–based difficulty grades to illustrate trends associated with increasing surgical complexity. With increasing surgical difficulty, patients tended to be older ($p < 0.001$) and exhibited higher anxiety levels ($p < 0.001$). BMI was also significantly elevated in the 'very difficult' group (median 25.80, $p < 0.001$). Root morphology distribution was significantly different across the groups ($p < 0.001$): Conical/Fused roots were clustered in the 'easy' group (77.5%), whereas bulbous (25 cases) and curved (31 cases) roots were heavily concentrated in the 'very difficult' group. P&G depth, ramus relationship, PDL width, and IAN risk all showed statistical significance ($p < 0.001$).

Table 2. Summary of operative time, surgical difficulty distribution, and perioperative complications.

Variables	Total (n = 250)
Operative time (minutes), M (Q_1, Q_3)	36.85 (20.70, 59.30)
Postoperative day 1 VAS pain score, M (Q_1, Q_3)	4.00 (2.00, 6.00)
Difficulty level, *n* (%)	
Easy	40 (16.00)
Moderate	53 (21.20)
Difficult	60 (24.00)
Very difficult	97 (38.80)
Perioperative complications, *n* (%)	
Dry socket	13 (5.20)
Hemorrhage	15 (6.00)
Nerve exposure	14 (5.60)
Root fracture	13 (5.20)
None	195 (78.00)

Note: Values are presented as numbers (percentages) for categorical variables and medians (interquartile ranges) for continuous variables. Operative time was used as a primary indicator of surgical difficulty. VAS, Visual Analog Scale.

Variable Selection

Table 4 summarizes the variable-screening phase, including the univariable logistic regression analyses and the preliminary multivariable model used to reduce the candidate predictor set. After adjustment in the preliminary multivariate model, traditional metrics such as P&G depth (Level B, p = 0.229), ramus relationship (class II, p = 0.590), PDL width (p = 0.133), BMI (p = 0.779) and mouth opening (p = 0.491) were no longer statistically significant. Ultimately, five variables were selected ($p < 0.05$), namely sex, Winter's angulation, root morphology, age, and MDAS score.

Logistic Regression Predictive Model

Table 5 presents the final multivariable prediction model used for nomogram development. Thus, Table 4 serves the purpose of variable screening, whereas Table 5 reports the final prediction model after variable reduction. Because the objective of Table 5 was predictive model construction rather than repeated inferential testing, the selected predictors were entered jointly into the final model even if some individual p-values changed slightly after simultaneous estimation. Collinearity diagnostics indicated no substantial multicollinearity among the retained predictors, with GVIF

Table 3. Comparison of variables across different surgical difficulty grades.

Variables	Total (n = 250)	Easy (n = 40)	Moderate (n = 53)	Difficult (n = 60)	Very difficult (n = 97)	Statistic	p
Age (years), M (Q_1, Q_3)	28.00 (24.00, 35.00)	23.00 (21.00, 24.00)	25.00 (22.00, 27.00)	28.00 (25.75, 31.00)	37.00 (30.00, 44.00)	H = 94.76	<0.001
BMI (kg/m^2), M (Q_1, Q_3)	23.90 (21.80, 26.00)	21.70 (20.70, 24.30)	22.60 (21.60, 24.40)	23.25 (21.85, 25.65)	25.80 (23.50, 27.20)	H = 43.17	<0.001
Mouth opening (mm), M (Q_1, Q_3)	44.00 (40.00, 47.00)	45.50 (42.25, 47.00)	46.00 (43.00, 47.00)	44.00 (41.00, 46.00)	42.00 (38.00, 46.00)	H = 14.43	0.002
MDAS score, M (Q_1, Q_3)	11.00 (9.00, 13.00)	9.00 (8.00, 12.00)	9.00 (8.00, 11.00)	12.00 (9.00, 15.00)	12.00 (9.00, 14.00)	H = 27.00	<0.001
Sex, n (%)						χ^2 = 8.61	0.035
Female	130 (52.00)	27 (67.50)	32 (60.38)	29 (48.33)	42 (43.30)		
Male	120 (48.00)	13 (32.50)	21 (39.62)	31 (51.67)	55 (56.70)		
Preoperative pericoronitis, n (%)						χ^2 = 53.89	<0.001
Acute	25 (10.00)	1 (2.50)	1 (1.89)	4 (6.67)	19 (19.59)		
Chronic	53 (21.20)	3 (7.50)	5 (9.43)	8 (13.33)	37 (38.14)		
None	172 (68.80)	36 (90.00)	47 (88.68)	48 (80.00)	41 (42.27)		
Winter's angulation, n (%)						χ^2 = 45.98	<0.001
Distoangular	43 (17.20)	1 (2.50)	4 (7.55)	12 (20.00)	26 (26.80)		
Horizontal	65 (26.00)	7 (17.50)	6 (11.32)	13 (21.67)	39 (40.21)		
Mesioangular	91 (36.40)	20 (50.00)	28 (52.83)	22 (36.67)	21 (21.65)		
Vertical	51 (20.40)	12 (30.00)	15 (28.30)	13 (21.67)	11 (11.34)		
P&G depth, n (%)						χ^2 = 75.05	<0.001
Level A	63 (25.20)	27 (67.50)	18 (33.96)	8 (13.33)	10 (10.31)		
Level B	115 (46.00)	7 (17.50)	26 (49.06)	41 (68.33)	41 (42.27)		
Level C	72 (28.80)	6 (15.00)	9 (16.98)	11 (18.33)	46 (47.42)		
P&G ramus, n (%)						χ^2 = 43.54	<0.001
Class I	112 (44.80)	30 (75.00)	31 (58.49)	26 (43.33)	25 (25.77)		
Class II	93 (37.20)	8 (20.00)	19 (35.85)	26 (43.33)	40 (41.24)		
Class III	45 (18.00)	2 (5.00)	3 (5.66)	8 (13.33)	32 (32.99)		
Root morphology, n (%)						χ^2 = 101.93	<0.001
Bulbous	40 (16.00)	1 (2.50)	2 (3.77)	12 (20.00)	25 (25.77)		
Conical/Fused	65 (26.00)	31 (77.50)	19 (35.85)	4 (6.67)	11 (11.34)		
Curved	63 (25.20)	4 (10.00)	5 (9.43)	23 (38.33)	31 (31.96)		
Divergent	82 (32.80)	4 (10.00)	27 (50.94)	21 (35.00)	30 (30.93)		
PDL width, n (%)						χ^2 = 58.28	<0.001
Normal	183 (73.20)	37 (92.50)	48 (90.57)	53 (88.33)	45 (46.39)		
Obscure	67 (26.80)	3 (7.50)	5 (9.43)	7 (11.67)	52 (53.61)		
IAN risk, n (%)						χ^2 = 32.64	<0.001
High risk	50 (20.00)	1 (2.50)	3 (5.66)	10 (16.67)	36 (37.11)		
Low risk	200 (80.00)	39 (97.50)	50 (94.34)	50 (83.33)	61 (62.89)		
Surgeon level, n (%)						χ^2 = 5.87	0.118
Resident	24 (9.60)	1 (2.50)	9 (16.98)	6 (10.00)	8 (8.25)		
Specialist	226 (90.40)	39 (97.50)	44 (83.02)	54 (90.00)	89 (91.75)		

Note: p-values were calculated using the Chi-square test (χ^2) for categorical variables, and the Kruskal–Wallis H test (H) for continuous variables.

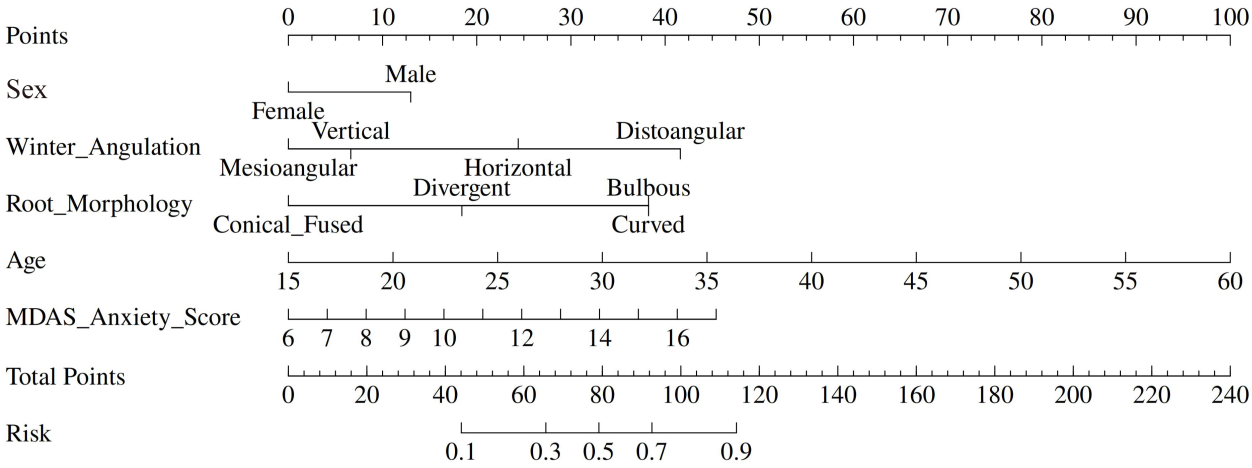

Fig. 1. Nomogram for predicting the probability of high-difficulty mandibular third molar extraction. To use the nomogram, locate the patient's value for each variable on the corresponding axis and draw a vertical line to the "Points" axis to determine the score. Sum the scores across all variables to obtain the "Total Points", then draw a vertical line down from the "Total Points" axis to the "Risk" axis to estimate the probability of high surgical difficulty. Abbreviation: MDAS, Modified Dental Anxiety Scale.

values ranging from 1.095 to 1.389 and adjusted GVIF values ranging from 1.029 to 1.151. Although the p-values of some variables (such as sex) were slightly different after the final adjustment, they were retained on grounds of their statistical significance during the screening stage to ensure the integrity of the predictive model. The final multivariate model was visualized as a nomogram (Fig. 1). By using "bulbous root" as the reference, the analysis revealed that "conical/fused roots" acted as a strong protective factor (odds ratio [OR] = 0.09, 95% confidence interval [CI]: 0.02–0.40, $p = 0.001$). Conversely, the risk associated with curved roots was statistically indistinguishable from bulbous roots (OR = 1.00, $p = 1.000$), placing them in the same high-risk tier. For every 1-point increase in MDAS score, the risk of high-difficulty rose by 30% (OR = 1.30, $p < 0.001$). Similarly, each additional year of age increased the risk by 15% (OR = 1.15, $p < 0.001$).

Model Performance

The model demonstrated strong performance (Fig. 2). In terms of discrimination, the ROC curve (Fig. 2A) showed an AUC of 0.91 (95% CI: 0.87–0.95). The bias-corrected calibration curve (Fig. 2B) closely aligned with the ideal diagonal, indicating accurate probability estimation. Regarding clinical utility, DCA (Fig. 2C) revealed that applying the model to guide clinical decisions provided a net benefit superior to "treat-all" or "treat-none" strategies across a wide threshold probability range (0.1–0.9).

Model Interpretability and Outcome Association Analysis

Fig. 3 shows a SHAP beeswarm plot, visually illustrating the feature importance ranking. Age was the most influential predictor, followed by Winter's angulation and root morphology. Notably, high anxiety scores (red dots) clearly contributed to predictions of high surgical difficulty.

In the secondary outcome association analysis (Table 6), operative time remained an independent risk factor for perioperative complications (OR = 1.03, $p = 0.017$) following adjustment for all baseline covariates (Model 3), implying a 3% risk increase per minute. However, this finding should be interpreted cautiously given the limited events-per-variable ratio in the fully adjusted model. Spearman's correlation analysis (Fig. 4) further revealed a strong positive correlation between operative time and VAS pain scores on postoperative day 1 ($\rho = 0.712$, $p < 0.001$).

Discussion

The current study developed a nomogram integrating factors such as root morphology and patient anxiety to predict MM3 tooth extraction difficulty, serving as an adjunct to traditional assessments based solely on tooth position. By incorporating SHAP-based interpretability, the model achieved high predictive accuracy (AUC = 0.91), linking both anatomical and psychological factors to clinical outcomes.

Root Morphology: The Biomechanical "Locking Effect"

While P&G classification focuses on coronal space, our results underscore the significant association of the root morphology with extraction difficulty. Data showed that curved and bulbous roots shared equivalent high-risk profiles (OR = 1.00). From a biomechanical perspective, apical hypertrophy (bulbous) or severe curvature creates an "undercut interlocking" effect within the deep alveolar socket. This morphology reduces the effectiveness of standard rotational forces, often necessitating extensive osteotomy to eliminate the undercut or complex root sectioning, and is therefore associated with prolonged operative time [24,25].

Table 4. Univariate logistic regression and preliminary multivariate model for high surgical difficulty.

Variables	Univariate		Multivariate	
	p	OR (95% CI)	*p*	OR (95% CI)
Sex				
Female		1.00 (Reference)		1.00 (Reference)
Male	0.005	2.12 (1.25~3.61)	0.038	2.95 (1.06~8.17)
Preoperative pericoronitis				
Acute		1.00 (Reference)		1.00 (Reference)
Chronic	0.390	0.49 (0.10~2.49)	0.065	0.14 (0.02~1.13)
None	0.002	0.10 (0.02~0.43)	0.070	0.18 (0.03~1.15)
Winter's angulation				
Distoangular		1.00 (Reference)		1.00 (Reference)
Horizontal	0.144	0.41 (0.12~1.36)	0.316	0.44 (0.09~2.20)
Mesioangular	<0.001	0.09 (0.03~0.28)	<0.001	0.07 (0.02~0.33)
Vertical	<0.001	0.10 (0.03~0.32)	0.007	0.12 (0.02~0.56)
P&G depth				
Level A		1.00 (Reference)		1.00 (Reference)
Level B	<0.001	5.34 (2.74~10.41)	0.229	1.93 (0.66~5.67)
Level C	<0.001	8.17 (3.75~17.78)	0.894	1.10 (0.28~4.33)
P&G ramus				
Class I		1.00 (Reference)		1.00 (Reference)
Class II	<0.001	2.72 (1.52~4.87)	0.590	0.77 (0.31~1.96)
Class III	<0.001	8.91 (3.27~24.23)	0.818	1.22 (0.23~6.39)
Root morphology				
Bulbous		1.00 (Reference)		1.00 (Reference)
Conical/Fused	<0.001	0.03 (0.01~0.10)	0.011	0.12 (0.02~0.62)
Curved	0.410	0.56 (0.14~2.24)	0.765	1.28 (0.25~6.65)
Divergent	0.002	0.13 (0.04~0.47)	0.116	0.30 (0.07~1.34)
PDL width				
Normal		1.00 (Reference)		1.00 (Reference)
Obscure	<0.001	6.12 (2.77~13.54)	0.133	0.30 (0.06~1.44)
IAN risk				
High risk		1.00 (Reference)		1.00 (Reference)
Low risk	<0.001	0.11 (0.04~0.33)	0.370	0.52 (0.13~2.16)
Surgeon level				
Resident		1.00 (Reference)		
Specialist	0.573	1.28 (0.54~3.01)		
Age	<0.001	1.23 (1.15~1.31)	<0.001	1.16 (1.07~1.26)
BMI	<0.001	1.34 (1.20~1.50)	0.779	1.03 (0.82~1.30)
Mouth opening	<0.001	0.90 (0.84~0.96)	0.491	0.96 (0.86~1.08)
MDAS score	<0.001	1.27 (1.14~1.40)	<0.001	1.36 (1.16~1.60)

Abbreviations: OR, odds ratio; CI, confidence interval.

Anxiety and Stress: Physiological Projection of Psychological Factors

Our study quantified the independent contribution of MDAS scores (OR = 1.30); this finding is consistent with the psycho-physiological interaction theory. High anxiety level activates the sympathetic nervous system and the HPA axis, triggering catecholamine release [26,27]. Physiologically, this manifests as elevated blood pressure (increasing bleeding risk and obscuring the field) and skeletal muscle tension (limiting mouth opening) [13,28]. Furthermore, consistent with central sensitization theory, anxiety lowers the pain tolerance threshold, necessitating frequent anesthetic top-ups and interrupting surgical flow [29]. As noted by Cardoso *et al.* [30], anxiety states are associated with intraoperative pain intensity, further elevating anesthetic requirements.

Model Discrimination and Limitations

Although this was a single-center retrospective study without external validation, the model showed good apparent discrimination in the present dataset (AUC = 0.91). A possible explanation is that the retained predictors are closely

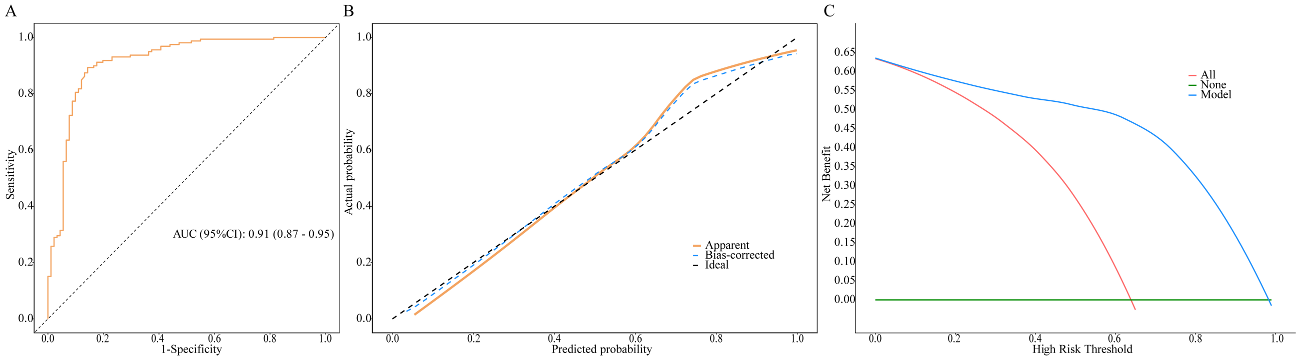

Fig. 2. Comprehensive validation of the prediction model performance. (A) The area under the curve (AUC) is 0.91 (95% CI: 0.87–0.95), indicating excellent discrimination. (B) In this calibration curve, the x-axis represents the predicted probability, and the y-axis represents the actual probability. The blue dashed line (bias-corrected) closely tracks the black dashed line (ideal), suggesting good calibration. (C) In decision curve analysis (DCA), the blue line represents the net benefit of using the model. The model provides a higher net benefit than the "treat-all" (red line) or "treat-none" (green line) strategy across a broad threshold probability range from 0.1 to 0.9.

Table 5. Final multivariate logistic regression model for predicting surgical difficulty.

Variables	Multivariate analysis				
	β	S.E.	Z	p	OR (95% CI)
Sex					
Female					1.00 (Reference)
Male	0.81	0.42	1.94	0.053	2.26 (0.99~5.15)
Winter's angulation					
Distoangular					1.00 (Reference)
Horizontal	–1.08	0.76	–1.41	0.158	0.34 (0.08~1.52)
Mesioangular	–2.61	0.73	–3.59	<0.001	0.07 (0.02~0.31)
Vertical	–2.19	0.76	–2.90	0.004	0.11 (0.03~0.49)
Root morphology					
Bulbous					1.00 (Reference)
Conical/Fused	–2.40	0.75	–3.18	0.001	0.09 (0.02~0.40)
Curved	–0.00	0.78	–0.00	1.000	1.00 (0.22~4.59)
Divergent	–1.24	0.71	–1.75	0.080	0.29 (0.07~1.16)
Age	0.14	0.04	3.94	<0.001	1.15 (1.07~1.23)
MDAS score	0.26	0.07	3.57	<0.001	1.30 (1.12~1.49)

Abbreviation: S.E., Standard Error.

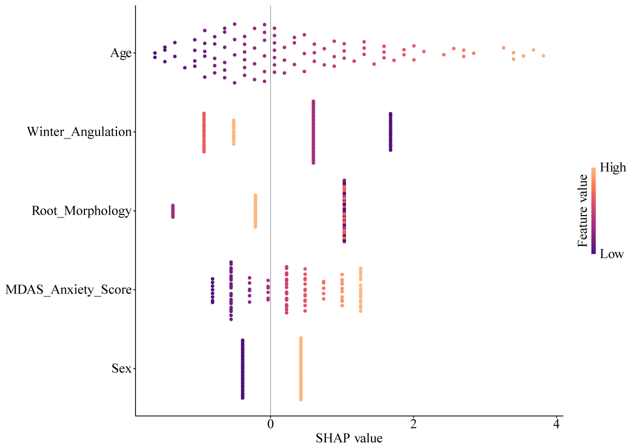

Fig. 3. SHAP beeswarm plot visualizing feature importance. Variables are ranked by importance from top to bottom. Each dot represents a single patient. The color indicates the feature value (red = high, purple = low). The x-axis (SHAP value) indicates the impact on the model output: positive values (to the right of '0') indicate a higher likelihood of high difficulty, while negative values (to the left of '0') indicate a lower likelihood. For example, red dots for MDAS score are distributed to the right, indicating that high anxiety scores increase the predicted difficulty. SHAP, SHapley Additive exPlanations.

linked to the mechanical resistance of mandibular third molar extraction. Because extraction is fundamentally a mechanical process of overcoming physical resistance, variables such as root morphology, angulation, and age-related bone changes may represent relatively stable structural determinants of surgical difficulty. This may help explain why the model performed well in the current cohort. Nevertheless, some degree of optimism or overfitting cannot be completely excluded, and external validation is still needed. Decision curve analysis (Fig. 2C) suggested potential clinical utility across a broad range of threshold probabilities.

Time-Dependent Trauma Mechanism

Our secondary outcome association analysis revealed a positive correlation between operative time and complication risk, which is consistent with the "time-dependent inflammation" hypothesis [31,32]. Prolonged tissue exposure may trigger a cascade of cytokines, such as interleukin-6 (IL-6) and tumor necrosis factor-alpha (TNF-α), thereby potentially exacerbating postoperative inflammation and pain [33,34]. This suggests that surgical efficiency extends beyond speed, encompassing effective control of inflamma-

Table 6. Sequential-adjustment logistic regression analysis of the association between operative time and perioperative complications.

Variables	Model 1		Model 2		Model 3	
	OR (95% CI)	*p*	OR (95% CI)	*p*	OR (95% CI)	*p*
Operative time (minutes)	1.06 (1.04~1.08)	<0.001	1.04 (1.02~1.07)	<0.001	1.03 (1.01~1.06)	0.017

Model 1 was unadjusted. Model 2 was adjusted for core demographic covariates (sex, age, and BMI). Model 3 was specified as an exploratory sensitivity model and was further adjusted for preoperative pericoronitis, Winter's angulation, P&G depth, P&G ramus relationship, root morphology, PDL width, IAN risk, surgeon level, mouth opening, and MDAS score. Given the limited number of complication events relative to the number of covariates, the results of Model 3 should be interpreted cautiously.

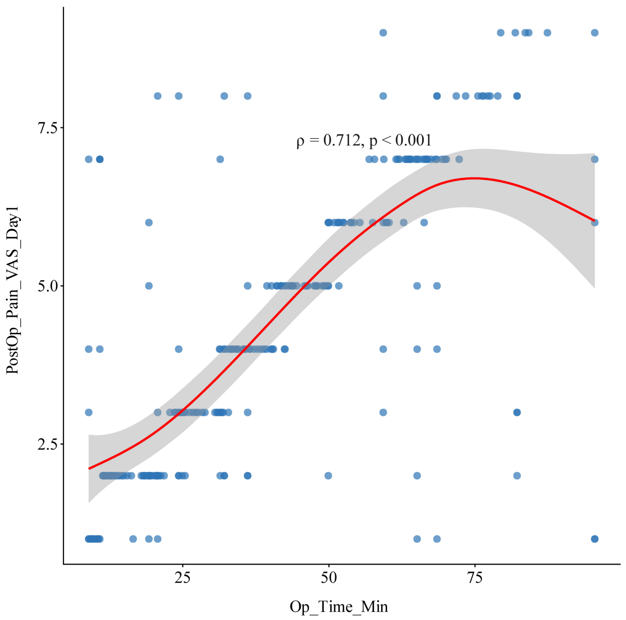

Fig. 4. Spearman's correlation analysis between operative time and postoperative pain. The scatter plot shows a strong positive correlation ($\rho = 0.712$, $p < 0.001$) between operative time and Visual Analog Scale (VAS) pain scores on postoperative day 1. The red line represents the smoothed trend line, and the gray shaded area indicates the 95% confidence interval.

tory response. For predicted high-difficulty cases, strategies to minimize operative time—such as using advanced piezoelectric instruments or prophylactic corticosteroids—may be considered.

Research Limitations

This study has several limitations. First, due to its single-center retrospective nature, bias that might affect extrapolation of the results could not be ruled out, despite the use of strict inclusion criteria and standardized radiographic assessments. Second, although operative time was used as a proxy for surgical difficulty and previous literature was considered, it can still be influenced by factors such as individual surgeon experience. Hence, this potential influence cannot be completely neglected and should be considered when interpreting the results. Third, although the validated MDAS tool was utilized to assess dental anxiety, it was measured at a single preoperative time point, limiting the ability to capture dynamic changes in perioperative anxiety. In addition, the fully adjusted complication model included a relatively large number of covariates relative to the number of events; therefore, some degree of model instability or overfitting cannot be completely excluded. Furthermore, because the model has not yet undergone external validation, its apparent discrimination in the present cohort should not be interpreted as definitive evidence of generalizability or freedom from model optimism.

Future Research Directions

Future research should strive to overcome these limitations through prospective, multicenter studies to improve the validity of the findings. Secondly, incorporating dynamic psychological assessment trajectories and objective physiological stress indicators at multiple time points may improve understanding of how psychological factors interact with surgical difficulty and may also help to clarify temporal relationships. Future prospective multicenter studies incorporating external validation, serial inflammatory markers, and dynamic psychological assessments are needed to determine whether the observed associations remain stable across settings and to better explore potential temporal mechanisms. Simultaneously, further improvements to the proposed nomogram through the incorporation of additional variables, as well as validation in multiple independent cohorts, are needed. With larger sample sizes, three-dimensional imaging data and advanced machine learning techniques, individualized preoperative risk prediction for mandibular third molar extraction.

Conclusions

Bulbous or curved root morphology, advanced age, high dental anxiety, Winter's angulation, and male sex were associated with high-difficulty mandibular third molar extractions. The nomogram constructed in this study, validated through calibration and DCA, may serve as an intuitive tool for preoperative risk stratification. By integrating psychological assessment with anatomical evaluation, it may facilitate a precise, patient-centered approach to surgical planning.

Availability of Data and Materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions

YW and FXX designed the research study. FXX performed the research. FXX analyzed the data. YW drafted the article. Both authors contributed to the critical revision of the manuscript for important intellectual content. Both authors read and approved the final manuscript. Both authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

This retrospective study was approved by the Ethics Committee of The First People's Hospital of Yongkang (Yongkang First People's Hospital) (Approval No: EC2025-LW-041-01(K)). Since this retrospective study involved no patient-identifiable information and ensured complete anonymization, the Ethics Committee waived the requirement for informed consent. This study was conducted in strict adherence to the ethical principles of the Declaration of Helsinki and the STROBE reporting guidelines.

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Conflict of Interest

The authors declare no conflict of interest.

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