Submitted: 12 August, 2025 Accepted: 05 November, 2025 Published: 03 May, 2026 DOI:10.22514/jocpd.2026.077

Journal of Clinical Pediatric Dentistry

ORIGINAL RESEARCH

A prediction model for the long-term survival of primary molars after Vitapex pulpectomy

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Abstract

Background: Although pulpectomy is recognized as the standard treatment for severe pulp pathologies, objective and quantifiable measures to predict primary molar survival after pulpectomy are limited. The aim of this study was to develop a predictive model for the long-term survival of primary molars after Vitapex pulpectomy using machine learning. **Methods**: This retrospective cohort study analyzed data from 212 pulpectomized primary molars. The DeepHit prediction model was developed based on significant prognostic factors identified through univariate Cox regression analysis. Calibration of the prediction model was evaluated, and further external validation was performed on 101 pulpectomized primary molars from multicenter cohorts. **Results**: Age at initial treatment, Frankl behavior score, arch type, presence of mucosal fistula, periapical lesion, and single-visit pulp treatment were significantly associated with survival rates. The weighted mean Brier score was 0.20, and an overall concordance index (C-index) was 0.73, indicating strong predictive accuracy. **Conclusions**: The DeepHit prediction model for primary molar pulpectomy in children under 9 years of age was successfully developed and showed clinical potential for predicting pulpectomy outcomes.

Keywords

Primary molars; Vitapex pulpectomy; Survival analysis; Machine learning; Prediction model

1. Introduction

Primary teeth are essential for the oral and systemic health of pediatric patients, influencing mastication, phonation, craniofacial development, and eruption of permanent teeth. For non-resorbing primary molars with severe pulp pathologies, such as irreversible pulpitis, pulp necrosis, or apical periodontitis, pulpectomy is the standard treatment recommended by the American Academy of Pediatric Dentistry and the Chinese Society of Pediatric Dentistry [1, 2]. This procedure maintains functional dentition, prevents premature tooth loss, and avoids related complications such as space loss and malocclusion [3].

Clinical studies have indicated that the survival rate of primary molar pulpectomy varies significantly, ranging from 31.1% to 89% during a 12- to 36-month follow-up period [4–10]. This variability is attributed to multiple factors, including follow-up duration, patient age, procedural standardization, root canal materials used, degree of root canal infection, and arch type. Previous studies have analyzed these factors, but their findings cannot be directly applied to assist in decision-making. Currently, primary care dentists rely on patient history, clinical examination, and radiological assessments for prognosis. However, these methods are subjective, depend on the clinician's experience, and lack objective and quantifiable measures. As many primary care dentists are non-specialists with limited exposure to pediatric endodontics, they often struggle to comprehensively evaluate the complex factors influencing prognosis.

Therefore, identifying the key determinants of primary molar survival after pulpectomy and developing an objective and reliable prognostic model is crucial. Such a model would enable primary care dentists to identify high-risk cases, implement targeted interventions, and facilitate informed communication with parents before treatment. Unfortunately, no validated prediction model exists in this field.

Survival analysis is a commonly used method to analyze time-to-event data in the medical field. It is mainly used in longitudinal studies to examine the patterns of events such as recurrence, death, or cure over time [11], and to identify potential sensitive or risk factors. Traditionally, survival analysis relies on models such as the Cox proportional hazards model and Kaplan-Meier curves. DeepHit is a more recent survival analysis model based on deep learning technology [12]. Unlike conventional approaches that rely on linear proportional hazards assumption, DeepHit employs a neural network architecture to model complex, non-linear relationships between covariates and survival outcomes without requiring strict assumptions. Its core innovation lies in its ability to perform non-parametric estimation of survival functions and handle competing risks. The model utilizes shared hidden layers to learn latent feature representations and event-specific sub-networks to generate dynamic, time-dependent risk predictions. This architecture enhances its capacity to capture time-varying effects and complex interactions among prognostic variables, making it particularly suitable for medical applications involving heterogeneous patient data and longitudinal follow-up [13, 14]. Similar neural network-based survival analysis techniques have shown superior results and have been well validated in some medical fields, such as oncology and Alzheimer's disease research [15, 16].

The aim of this study was to develop and validate a DeepHit-based prognosis prediction model for primary molar pulpectomy. To achieve this, we collected and analyzed clinical data to identify critical factors influencing postoperative outcomes and further refined the model through validation with external center data. A key focus of this work was to emphasize the model's potential clinical utility for primary care dentists—specifically, its ability to provide accurate and objective prognosis assessments, as well as evidence-based treatment recommendations to support routine clinical decision-making in primary care settings.

2. Materials and methods

2.1 Patients and methods

2.1.1 Patient selection

This was a retrospective cohort study, and data were collected from digital medical records from January 2018 to December 2020. Children under 9 years of age who had undergone primary molar pulpectomy under local anesthesia. The inclusion criteria were as follows:

(1) Primary molars treated for irreversible pulpitis, pulp necrosis, or apical periodontitis in medically healthy children with complete medical records at treatment and follow-up visits.

(2) Pre-treatment periapical radiographs indicating no involvement of the permanent successor and minimal ($<$1/3 of the root length) or no root resorption.

(3) Radiographic examinations available post-treatment and at least during one follow-up visit.

(4) Pulpectomy was performed on or before 30 June 2023. This ensured that all included patients had a minimum follow-up duration of 18 months, from the date of treatment to the end of the data collection period (31 December 2024). Furthermore, the interval between any two consecutive follow-up visits for an individual patient should not have exceeded 1 year.

The exclusion criteria were as follows:

(1) Children with chronic illnesses that impact dental hygiene.

(2) Abnormal or calcified teeth.

2.1.2 Clinical protocol

Periodontal anesthesia was administered using articaine with epinephrine injection (X-31, Bilan, Mérignac, France) prior to isolating the tooth with a rubber dam. The procedure involved the following steps: TC21 bur was used to open the pulp chamber and remove prominent buccolingual inverts; TF31 bur was employed to prepare the pulp surface; BR46 round bur was used to remove caries on the adjacent surface; lifting and pulling techniques were applied to remove the entire pulp roof; and Endo Z bur was used to fully reveal the top of the pulp chamber. The root canal was first probed with an #8 stainless steel K-file (Dentsply M-Access, Sirona, USA), unclogged, and followed by #10 and #15 K-files. Upper root canals were accessed using an open-ended file (2004) from the M3 deciduous set (Beefan Medical, Chongqing, China). The working length was determined using a MORITA ZX mini apex locator (Morita Medical, Kyoto, Japan), stopping at a reading of "1". Preparation was done to this length using the red (2504) and blue (3004) files from the M3 set. After each file, the canals were irrigated with 1% sodium hypochlorite using a side-vented needle, inserted to approximately 2 mm short of the working length. After preparation, paper tips were used to aspirate and dry the canal. Vitapex (B4J1, Neo Dental Chemical Products Co. Ltd., Tokyo, Japan) was injected 2–3 mm short of the apical foramen, with the needle advanced as far as possible. The paste was delivered to the root tip and allowed to back flow to the canal opening. Upon observing backflow, the syringe needle was withdrawn. The pulpal cavity was cleaned with a dry cotton ball and filled with FUJI IX glass ionomer cement (G.C. Dental Industrial Corporation, China). A metal preformed crown (3M ESPE, USA) was selected, and bonded using glass ionomer cement (3M China Limited, China). Radiographs were obtained to assess the root canal filling. If parents requested that metal crowns not be used, the cavity was directly filled with FUJI IX glass ionomer. All clinical procedures in this study were performed by the first author.

2.1.3 Data collection

Dental records were retrieved from an electronic clinical database, and factors potentially affecting treatment outcome (identified through clinical experience or literature review) were extracted. These variables included gender, birth date, age at initial treatment ($<$5 years, 5–7 years, or $\geq$7 years), chief complaint, Frankl behavior score, arch type (upper or lower), tooth type (first or second primary molar), mucosal condition (presence of mucosal fistula at the time of or at any point before treatment), periapical lesion, number of visits, and crown restoration materials.

2.1.4 Assessment of treatment outcome

Treated teeth were evaluated using clinical records and follow-up periapical radiographs. Clinical failure of pulpectomy was defined as either the premature loss of the primary tooth or presence of a gingival fistula. Premature loss was determined using the contralateral homonymous tooth as a reference. Specifically, a tooth was considered prematurely lost if it exfoliated earlier than its contralateral counterpart. In the absence of clinical failure, further assessment was conducted using periapical radiographs.

Radiographs of the treated teeth were obtained using #0 film with a clamp and the parallel projection method. To mitigate selection bias, all treated teeth were assessed, regardless of the clarity of the periapical radiographs. Two pediatric dentists with over 5 years of clinical experience independently assessed the radiographs. In cases of disagreement, reevaluations were performed to reach a consensus.

Casas *et al*. [17] reported that Vitapex is easily resorbed with minimal side effects; therefore, even if resorption occurs, the treatment is not to be deemed a failure [18]. Periapical radiographs were assessed for the clarity of the periodontium, density in the apical or furcation area, abnormal root resorption, resorption of intracanal medicament, and continuity of the white line around the succeeding permanent tooth. The criteria for classifying teeth into Normal (N), Healed (H), Pathosis (P_0), Pathology (P_x) categories are presented in Fig. 1. Teeth classified as N, H, or P_0 were considered as surviving, whereas those classified as P_x were considered failures. The survival rate was calculated as the ratio of surviving teeth to the total number of teeth assessed.

Follow-up data were collected up to the study censor date of 31 December 2024. For the survival analysis, the "survival time" for each tooth was defined as the period from the date of pulpectomy (time zero) to the occurrence of a failure event. A tooth was censored if at the last recorded follow-up visit on or before 31 December 2024, it remained functional without any signs of failure. This censoring approach accounted for teeth that had not failed by the end of the study or were lost to follow-up.

2.2 Statistical analysis

All statistical analyses were performed using R software 4.2.1. For continuous variables, the median and interquartile range were used for non-normally distributed data, whereas the mean and standard deviation were used for normally distributed data. Additionally, proportions were calculated for categorical data. For the univariate analysis of categorical variables, either Fisher's exact test or the chi-square test was used. The log-rank test was used to analyze differences in Kaplan-Meier survival curves, which were generated to evaluate differences in survival probabilities among various groups based on variables extracted.

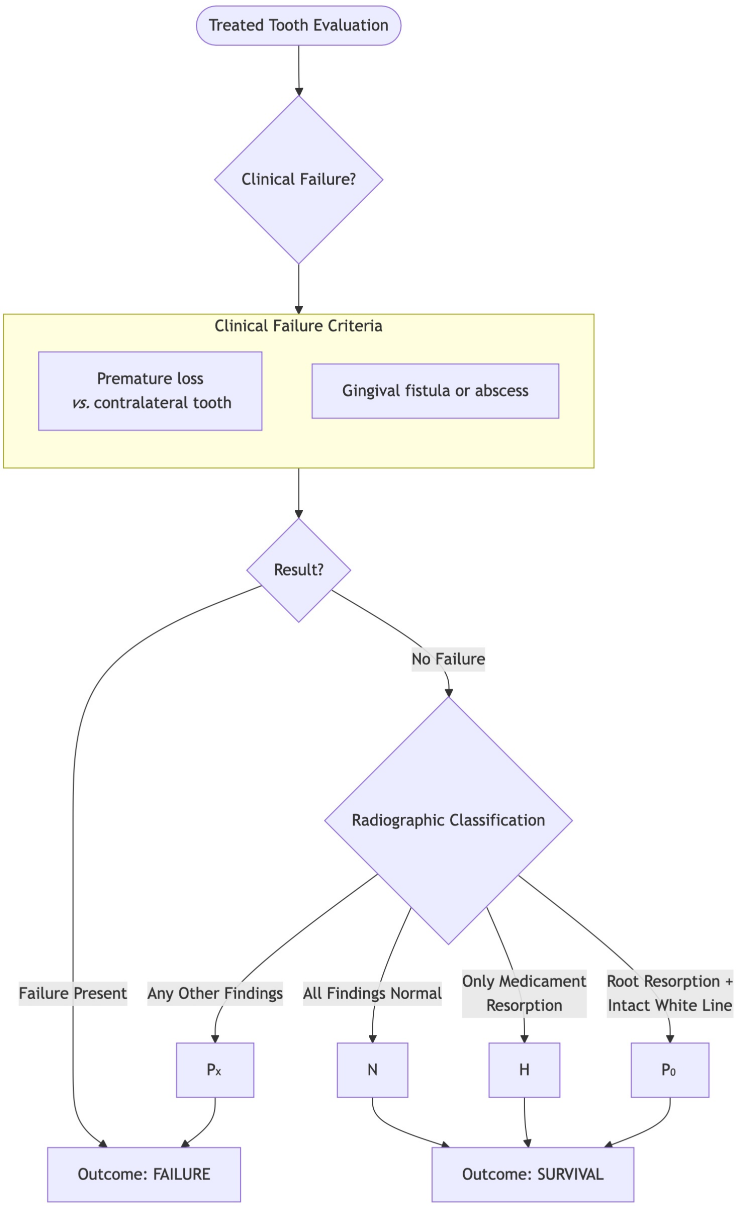

FIGURE 1. Criteria for classifying teeth into Normal (N), Healed (H), Pathosis (P_0), Pathology (P_x).

To assess the effect of each variable on post-treatment tooth survival and to quantify the level of risk, univariate Cox regression analysis was used. In this study, the end event was defined as failure of pulpectomy treatment based on the examination findings corresponding to category P_x. Censoring occurred if the patient was lost to follow-up before an outcome event was observed, or the study end date was reached without evidence of failure. The survival time for teeth with events was calculated from the date of treatment to the date of the event. For censored teeth, observation was terminated at the date of the last follow-up or the date the patient was lost to follow-up. The statistical significance level for this study was set at $p < 0.05$. After completing the Cox univariate analysis, the risk factors identified were selected as input features for the development and evaluation of the prediction model.

To provide a benchmark for comparing the performance of the DeepHit model, a traditional multivariate Cox proportional hazards model was also developed using the same set of significant prognostic factors identified from the univariate analysis. This Cox model was fitted and evaluated on the same dataset and using the same cross-validation splits as the DeepHit model to ensure a fair comparison.

2.3 Deep learning-based dynamic prediction model

2.3.1 Model development

The dataset was largely complete, with minimal missing data. For the missing values, we performed multiple imputations using the Multivariate Imputation by Chained Equations (MICE) package in R (v3.13.0). The MICE package was employed for multiple imputations to handle missing data, as it provides flexibility by using chained equations to impute different variable types appropriately and accounts for the uncertainty inherent in missing data, yielding more reliable statistical inferences [19]. Next, we developed a dynamic prognostic prediction model for treatment failure using the DeepHit deep learning framework.

Significant prognostic factors identified through univariate Cox regression analysis were selected as the model inputs. To ensure the robustness of our model, we assessed the sample size adequacy based on the criterion of Events Per Variable (EPV). With 123 observed failure events and 8 predictors, the dataset yielded an EPV of 15.3, which comfortably exceeds the recommended minimum threshold of 10 EPV for prognostic model development, thereby reducing the risk of model overfitting. Categorical variables were subjected to one-hot encoding to preserve categorical information integrity, whereas continuous variables were standardized using Z-score normalization. The model hyperparameters were optimized employing a 5-fold cross-validation scheme to ensure robust generalization performance through systematic validation procedures. The specific network architecture was a multilayer perceptron (MLP) with an input dimension matching the number of selected prognostic features. It consisted of two fully connected hidden layers, each with 32 nodes and followed by the Rectified Linear Unit (ReLU) activation function. Batch normalization was applied before the activation in each hidden layer. To regularize the model and prevent overfitting, a dropout rate of 0.1 was used after each hidden layer, and the Adam optimizer was employed with an L2 weight decay of 1×10^{-5}. To ensure the reproducibility of our results, a fixed random seed (1234) was used for all random number generators involved in model initialization and training. Notably, we implemented a patient-level blocking strategy during the dataset splitting for cross-validation.

2.3.2 Model evaluation

In this study, the time-stratified Brier score (BS) was primarily employed to quantify the calibration of the prediction. BS was calculated using the following formula (Eqn. 1):

$$Brier\,(t) = \frac{1}{N}\sum_{i=1}^{N}\left(\hat{S}\,(tx_i) - I\,(T_i > t)\right)^2 \qquad (1)$$

Where $I\,(T_i > t)$ is the time indicator function reflecting the actual survival status of an individual at time t. $\hat{S}\,(t|\,x_i)$ represents the model-predicted survival probability at time t, while also computing weighted averages across different time intervals. In general, the BS is used to measure the degree of calibration between the predicted probability and the actual result. The values range from 0 to 1, with smaller scores indicating better performance of the model [20].

2.3.3 External validation of the model

To further validate the generalizability of the model, an independent external validation was performed using treatment and follow-up data collected from external multicenter cohorts. The preprocessing workflow for these datasets strictly adhered to the procedures applied to the training cohort, including feature standardization, missing value imputation, and covariate harmonization. Data were collected from the Pediatric Dentistry Department of Huayu Dental Clinic between June 2019 and November 2021.

3. Results

3.1 Descriptive analysis

A total of 212 primary molars in 120 children (70 boys and 50 girls) treated between January 2018 and December 2020 were analyzed. Their average age at the first visit was 5.29 years, ranging from 3 to 8 years.

The distribution of survival and failure in pulpectomy based on the predictor variables is presented in Table 1. Pulpectomy was mostly performed in 131 boys (61.8%) and children aged 5–7 years (51.9%). First primary molars (63.2%) were the most commonly treated teeth, and the treated teeth were predominantly located in the lower arch (60.4%). Most teeth did not have a history of pain (77.8%), mucosal fistulas (92.0%), or periapical lesions (59.0%). The majority of teeth that underwent pulpectomy received single-visit pulp treatment (92.5%) and were restored with stainless steel crowns (SSC) (93.4%). The distribution of Frankl behavior scores for the treated teeth was relatively even: 41 (19.3%) with a score of 1; 59 (27.8%) with a score of 2; 56 (26.4%) with a score of 3; and 56 (26.4%) with a score of 4.

The follow-up period ranged from 56 to 1761 days, with an

TABLE 1. The baseline characteristics of the training and external validation cohorts.

Variables	Test N (%)	Train N (%)	*p* value
	101	212	
Gender			
Boy	56 (55.4)	131 (61.8)	0.369
Girl	45 (44.6)	81 (38.2)	
Age (yr)			
<5	30 (29.7)	59 (27.8)	
5–7	58 (57.4)	110 (51.9)	0.245
≥7	13 (12.9)	43 (20.3)	
Chief complaint			
Pain after eating	4 (4.0)	29 (13.7)	
Spontaneous pain	12 (11.9)	18 (8.5)	0.027
No pain	85 (84.2)	165 (77.8)	
Tooth type			
1st primary molar	48 (47.5)	134 (63.2)	0.011
2nd primary molar	53 (52.5)	78 (36.8)	
Arch type			
Maxillary	45 (44.6)	84 (39.6)	0.460
Mandibular	56 (55.4)	128 (60.4)	
Presence of mucosal fistula			
Yes	2 (2.0)	17 (8.0)	0.067
No	99 (98.0)	195 (92.0)	
Periapical lesion			
Yes	24 (23.8)	87 (41.0)	0.005
No	77 (76.2)	125 (59.0)	
SSC			
Yes	99 (98.0)	198 (93.4)	0.146
No	2 (2.0)	14 (6.6)	
Single-visit pulp treatment			
Yes	100 (99.0)	196 (92.5)	0.034
No	1 (1.0)	16 (7.5)	
Frankl behavior score			
1	6 (5.9)	41 (19.3)	
2	23 (22.8)	59 (27.8)	0.005
3	39 (38.6)	56 (26.4)	
4	33 (32.7)	56 (26.4)	
Survival time (d)	762.89 ± 313.26	763.63 ± 375.04	0.986

SSC, stainless steel crowns.

average of 756 days. Based on the clinical and radiographic assessments, 11 teeth (5.2%) were classified as N, 53 (25.0%) as H, 25 (11.8%) as P_0, and 123 (58.0%) as P_x. Of these, 53 teeth exhibited only imaging abnormalities, whereas 70 exhibited both clinical and imaging abnormalities.

The baseline demographic and clinical characteristics of the external cohort are presented alongside the training cohort in Table 1, which reveals expected differences in case-mix between the cohorts, particularly in Frankl behavior scores and the prevalence of preoperative infections. These significant differences in clinical features provided a rigorous test of the model's robustness.

The survival rates of the teeth during the follow-up period are shown in Fig. 2. The survival rates were 86.8% and 49.5% at 12 and 24 months, respectively. At 36 months, 23.6% of the primary molars remained functional, decreasing to 3.3% by 48 months. Representative radiographs showing survival and failed cases are presented in Fig. 3.

3.2 Kaplan-Meier curves

Univariate analysis revealed that variables such as "age at initial treatment", "Frankl behavior score", "arch type", "presence of mucosal fistula", "periapical lesion", and "single-visit pulp treatment" were significantly associated with the survival rate ($p < 0.05$). The Kaplan-Meier curves illustrated survival discrepancies over time, based on relevant prognostic factors (Fig. 4).

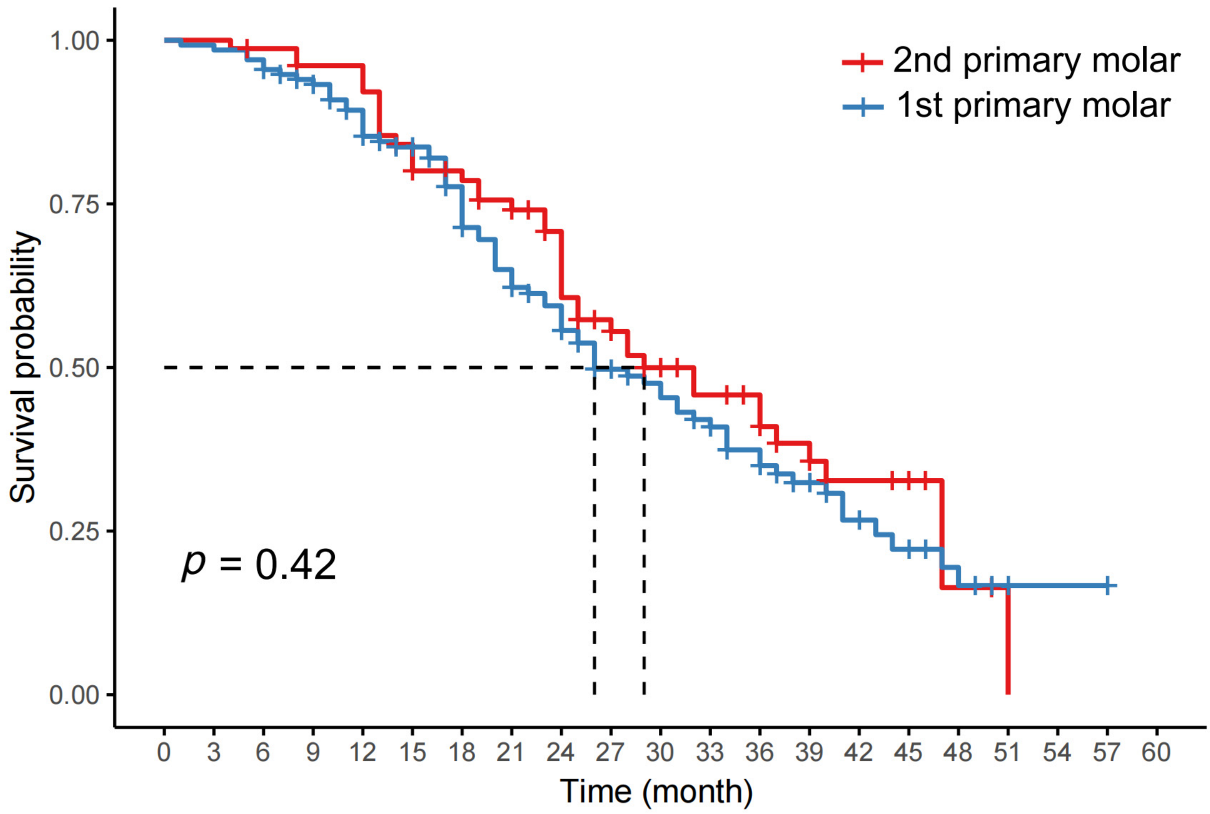

FIGURE 2. Survival rates of the teeth during the follow-up period in different tooth type.

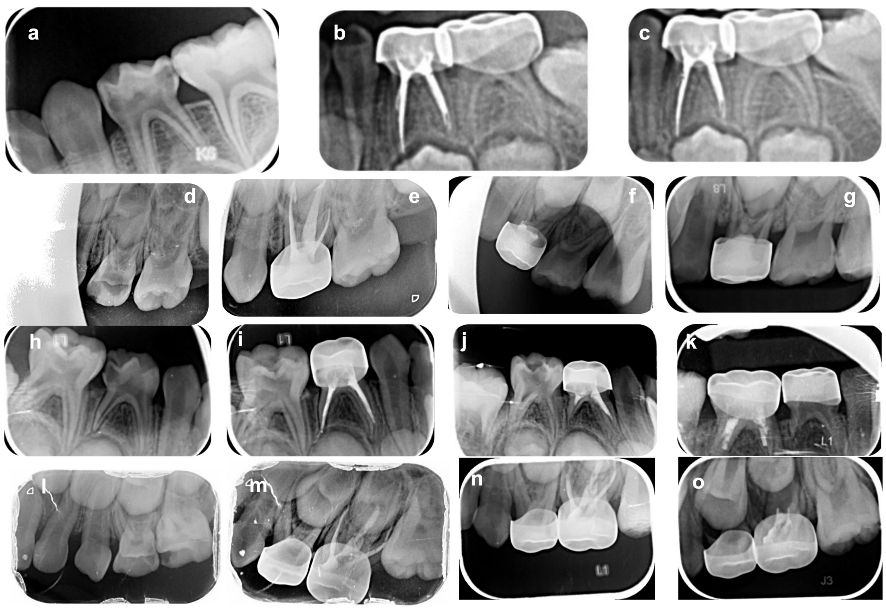

FIGURE 3. Representative radiographs showing survival and failed cases. (a) Pre-treatment radiograph: 5Y3M, F, #74, N. (b) Twelve-month follow-up radiograph. (c) Twenty-nine-month follow-up radiograph showing clear periodontium and no periapical radiolucency in the periapical region. (d) Pre-treatment radiograph: 4Y2M, M, #64, H. (e) Immediate postoperative radiograph. (f) Thirty-five-month follow-up radiograph. (g) Fifty-eight-month follow-up radiograph showing intracanal filling resorption without periapical lesion. (h) Pre-treatment radiograph: 5Y2M, M, #84, P_0. (i) Immediate postoperative radiograph. (j) Five-month follow-up radiograph. (k) Twenty-month follow-up radiograph showing root resorption, but presence of continuous bony white line of the permanent tooth. (l) Pre-treatment radiograph: 4Y4M, F, #65, P_x. (m) Immediate postoperative radiograph. (n) Twelve-month follow-up radiograph. (o) Twenty-three-month follow-up radiograph showing periapical low-density radiolucency and discontinuous bony white line of the permanent tooth.

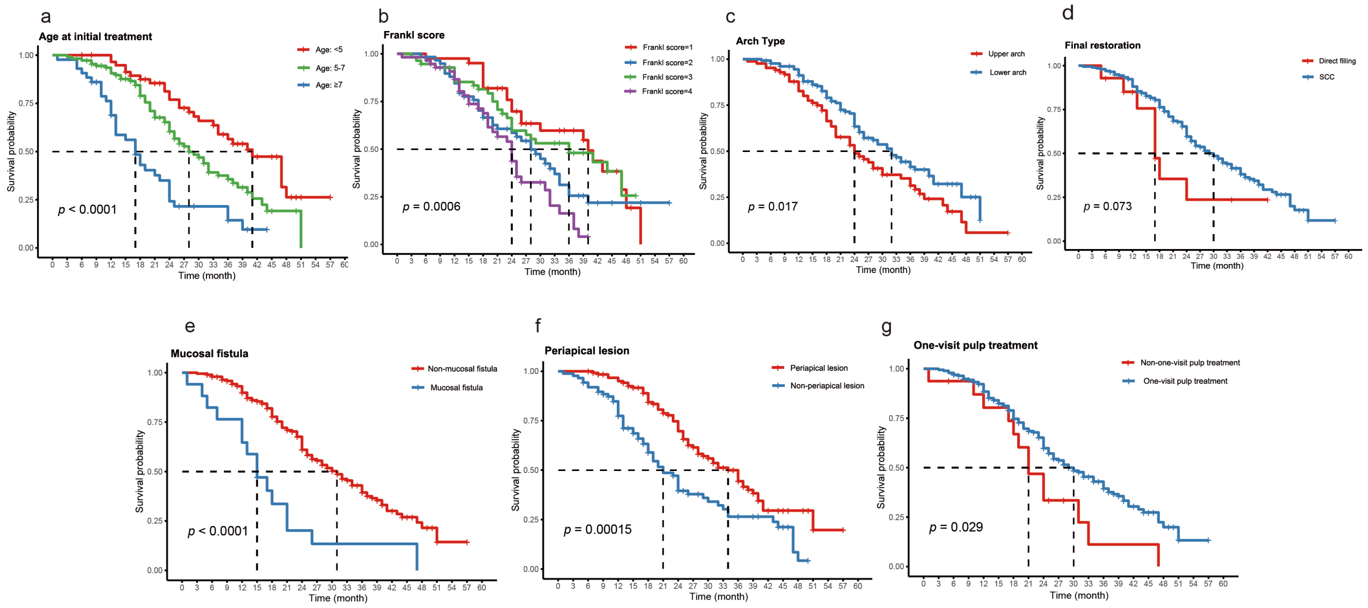

FIGURE 4. Kaplan-Meier curves illustrating survival discrepancies over time, based on relevant prognostic factors. (a) survival outcomes stratified by age at initial treatment. (b) survival outcomes stratified by Frankl score. (c) survival outcomes stratified by arch type. (d) survival outcomes stratified by crown restoration materials. (e) survival outcomes stratified by mucosal condition. (f) survival outcomes stratified by periapical lesion. (g) survival outcomes stratified by number of visits. SSC: stainless steel crowns.

3.3 External validation performance of prediction models

The generalizability of the DeepHit prediction model was assessed using the independent external validation cohort. To rigorously evaluate the prediction model, we compared its performance against a multivariate Cox proportional hazards model, incorporating the same significant prognostic factors. Model discrimination was assessed using the concordance-index (C-index) and area under the receiver operating characteristic curve (AUC). Calibration was evaluated using the time-dependent Brier score.

The DeepHit model achieved an overall C-index of 0.73, outperforming the Cox model (C-index: 0.67). Analysis of time-dependent receiver operating characteristic curves (Fig. 5a–d) revealed that the DeepHit model's advantage was particularly pronounced in predicting short-term failure. For instance, the AUC for predicting 1-year failure was 0.844 for the DeepHit model compared with 0.774 for the Cox model. However, the predictive accuracy for long-term outcomes (>2 years) was limited for both models, with AUCs falling below 0.7 (**Supplementary Fig. 1**). As the follow-up time increased, the C-index at different time points also decreased (Table 2).

TABLE 2. C-index analysis of DeepHit model and Cox models at different time points.

	1-year	2-year	3-year	4-year
DeepHit	0.831	0.684	0.513	0.493
Cox	0.753	0.668	0.678	0.677

The overall weighted mean Brier score was 0.20 for the DeepHit model and 0.18 for the Cox model. The time-dependent trajectory of the Brier score showed that prediction errors for both models increased over time, as expected in long-term survival analysis. Notably, the DeepHit model's Brier score increased at a faster rate beyond 30 months, contributing to its slightly higher overall weighted score (Fig. 5e,f). These findings suggest that while DeepHit excels at short-term risk stratification, its performance in long-term forecasting is more volatile. The comparable performance of the Cox model in terms of Brier score, despite its lower discriminative ability, may be attributed to the proportional hazards assumption providing a stable, albeit less nuanced, baseline for probability estimation over time.

3.4 Interpretability of the DeepHit model using SHAP analysis

To elucidate the contribution and directional effect of each prognostic factor in the DeepHit model, SHAP (SHapley Additive exPlanations) analysis was performed. Fig. 6 illustrates the SHAP values, ranking the features by their overall importance in the model's predictions. The top three contributors were age at initial treatment, arch type, and presence of periapical lesion. The result confirmed the trends observed in the univariate Kaplan-Meier analysis. Specifically, mid-range ages were predominantly associated with negative SHAP values, indicating a protective effect and a lower risk of failure. Mandibular molars showed negative SHAP values, suggesting a lower risk of failure compared to maxillary molars. Conversely, the presence of a periapical lesion exhibited positive SHAP values, confirming its role as a significant risk factor for failure. Furthermore, higher Frankl behavior score was

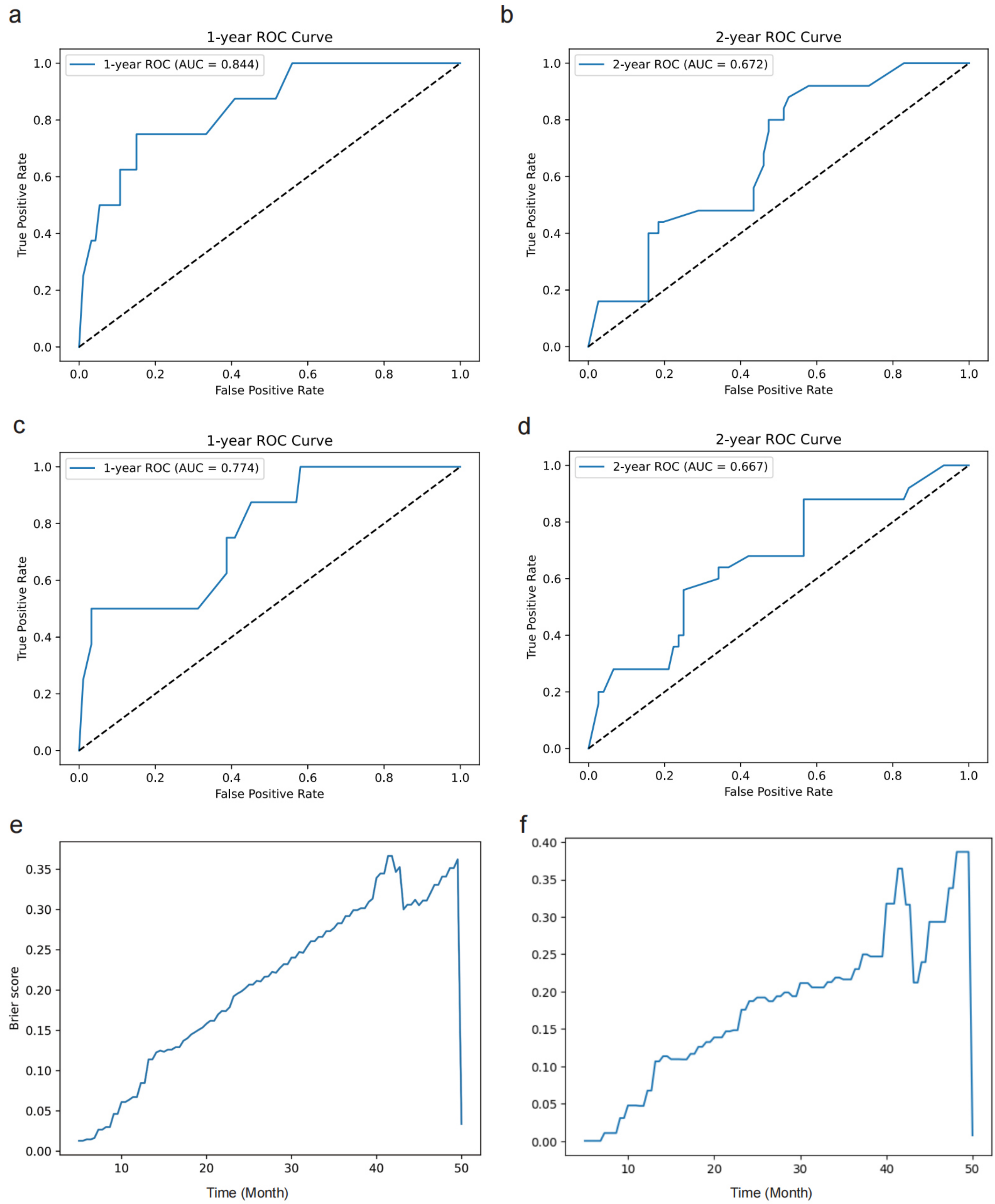

FIGURE 5. Predictive performance evaluation of DeepHit and Cox proportional hazards models. (a) Time-dependent Receiver Operating Characteristic (ROC) curve for the DeepHit model at 1 year (Area Under the Curve, AUC = 0.844). (b) ROC curve for the DeepHit model at 2 years (AUC = 0.672). (c) ROC curve for the Cox model at 1 year (AUC = 0.774). (d) ROC curve for the Cox model at 2 years (AUC = 0.667). In panels a–d, the dashed diagonal line indicates the reference line of no discrimination (AUC = 0.5). (e) Time-dependent Brier score for the DeepHit model, showing the model's calibration error over time (in months). A lower Brier score indicates better accuracy. (f) Time-dependent Brier score for the Cox model over the same period.

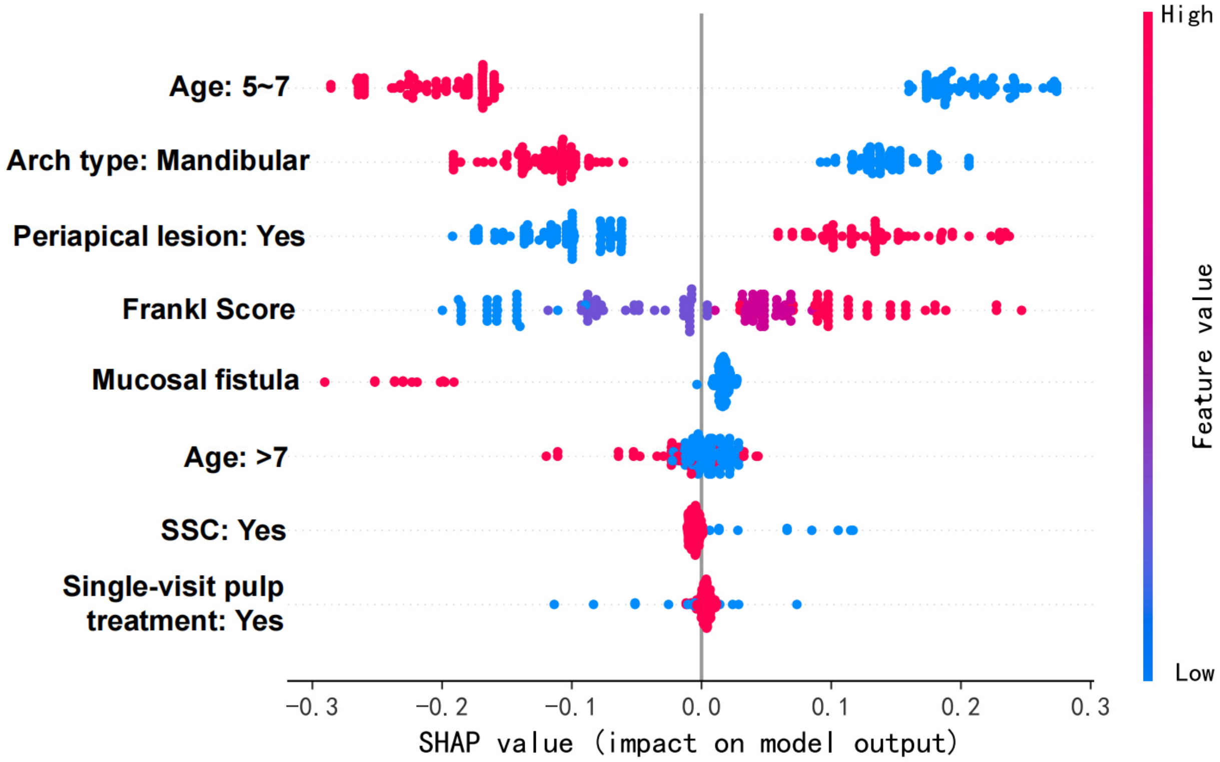

FIGURE 6. SHAP summary plot. Each point represents a single prediction. The position on the x-axis is the SHAP value (impact on model output: positive values increase the risk of failure, whereas negative values decrease it). The colors represent the feature value from low (blue) to high (red). Overlapping points are jittered in the y-axis to show density. SHAP: SHapley Additive exPlanations; SSC: stainless steel crowns.

correlated with positive SHAP values, suggesting that reduced patient cooperation was not associated with an increased risk of failure.

4. Discussion

In this study, variables influencing tooth survival following primary molar pulpectomy were first identified using univariate Cox regression analysis, and their clinical significance was evaluated. Subsequently, these influencing factors were used to construct a prediction model. This study employed an integrated BS to assess the importance of these features, with lower BS values indicating better predictive performance [20]. The second aspect of this study was the application of this model to generate predicted survival curves for individual affected teeth based on their specific conditions and treatment characteristics. This model could help inform the legal guardians of pediatric patients and the professionals treating them about the likelihood of experiencing adverse events following pulpectomy. It could also assist non-specialist doctors at the primary level to identify high-risk teeth and optimize treatment plans accordingly. Additionally, it could serve as an important auxiliary tool for clinical decision-making regarding pediatric patients.

The prognosis of primary molar pulpectomy is synergistically influenced by the properties of the materials, patient factors, and treatment strategies. Among root canal filling materials, zinc oxide eugenol (ZOE) is known to resist foreign body giant cell resorption. From a clinical perspective, such resistance can result in ectopic eruption of the succedaneous tooth, which in turn can lead to outcomes such as anterior crossbite and palatal eruption [3, 14]. Hence, Vitapex was chosen in the present study, as it can be placed up to the apical area using its delivery tube, is a ready-to-use product, and is readily available [3, 21].

Regarding patient factors, age appears to be the most important variable affecting the prognosis of primary molar pulpectomy. In older children, the failure rate increases due to changes in root canal morphology [4, 22] and physiological root resorption [23–25]. The degree of infection in the apical area is strongly associated with the survival or failure of treatment. Owing to limited operating field of view and greater difficulty in diagnosis, the survival rate of maxillary molars is lower than that of mandibular molars. The presence of a mucosal fistula tends to increase the risk of treatment failure. The preoperative infection status is believed to have a greater impact on prognosis than the treatment method [4, 6, 8].

Notably, children with a Frankl behavior score of 1 had the highest tooth survival rates, with approximately 50% of teeth remaining functional after 40 months, aligning with a study on pulpectomy under general anesthesia [8, 10]. Another study comparing survival rates in children under 5 years of age undergoing pulpectomy under general and local anesthesia confirmed this. The cumulative 5-year survival rates were not significantly different between the groups [26]. Most children with low cooperation scores were in the younger age group, highlighting the association between younger age and higher survival rates in retaining pulpectomized primary molars. Thus, even for young children with low cooperative ability, a high survival rate can still be achieved through behavior management and standardized treatment protocols. These findings confirm that the prognosis of pulpectomy is determined by the interaction of multiple factors, providing a new basis for clinical decision-making.

The DeepHit model leverages the heterogeneous interactions between individual patient characteristics and treatment-related variables to generate personalized survival curves for each patient. By dynamically modeling the complex interplay of covariates, it captures patient-specific risk trajectories, thereby providing tailored prognostic estimates that reflect individualized clinical profiles and treatment effects, which hold potential in clinical applications.

One of the notable aspects of this study is the use of state-of-the-art survival analysis techniques to construct a dynamic and personalized prediction model for assessing the prognosis of primary molar pulpectomy in children under 9 years of age. This model showed promising performance, allowing the generation of prognostic estimates in advance. In a clinical context, identifying cases with higher predicted risk could provide a basis for closer monitoring of critical factors and proactive intervention; additionally, the model's output might serve as a reference to facilitate more effective communication between dentists and patients' legal guardians, enabling informed treatment decisions tailored to each child's unique needs.

The limitations of this study are as follows: This model is applicable only to cases treated using Vitapex as the root canal filling material and may not be directly applied to cases in which other materials were used. Another limitation was that the time intervals for periapical radiography during follow-up were inconsistent, which may have caused delays in detecting teeth that required extraction and consequently led to an overestimation of survival times [1, 27]. This highlights the importance of follow-up imaging after pulpectomy. Additionally, several predictor variables showed highly skewed distributions: mucosal fistula was absent in 92.0% of cases, SSC restoration was used in 93.4% of cases, and single-visit treatment was performed in 92.5% of cases. Therefore, the significance of these variables should be interpreted with caution. The small size of minority subgroups undermines the stability of estimates and the robustness of inferences, reducing statistical power and increasing susceptibility to random variations. In the future, prospective studies integrating data from periapical radiographs with clinical data are required to establish a more comprehensive prediction model.

This study demonstrated comparable survival rates for primary molars treated with Vitapex under local anesthesia. Approximately half of the treated molars were preserved 2 years post-treatment. Among children under 5 years of age, the survival rate for primary molars was higher, with nearly 50% of teeth remaining functional after 40 months. The age at initial treatment, and the presence of a mucosal fistula were shown to be strong predictors of the prognosis of pulpectomy.

This DeepHit model serves an objective prognostic tool for primary dental care, transcending reliance on subjective judgment. By generating individualized risk assessments, it enables clinicians identify high-risk cases at an early stage and supports shared, informed decision-making with parents.

5. Conclusions

This study successfully developed and validated the DeepHit prediction model for primary molar pulpectomy in children under 9 years of age. Advanced machine learning algorithms were used to construct and validate the model with external center data. We intend to make the model available on a public server to facilitate clinical translation. This prediction model is expected to enable more accurate identification of high-risk cases, improve treatment decision-making in clinical practice, and become a useful tool for communication with the parents of pediatric patients.

ABBREVIATIONS

C-index, concordance-index; N, Normal; H, Healed; P_0, Pathosis; P_x, Pathology; SSC, stainless steel crowns; MICE, Multivariate Imputation by Chained Equations; EPV, Events Per Variable; MLP, multilayer perceptron; ReLU, Rectified Linear Unit; BS, Brier score; AUC, Area Under the Curve; SHAP, SHapley Additive exPlanations; ZOE, zinc oxide eugenol.

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

LX and DZ—designed the research study. LX and XZ—performed the research. LY—analyzed the data. LX and LY—wrote the manuscript. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The study protocol was approved by the Institutional Review Board of Deyang People's Hospital (approval no: 2024-04-017-K01). All procedures complied with the principles of the Declaration of Helsinki. The requirement for patients' informed consent was waived by Deyang People's Hospital.

ACKNOWLEDGMENT

We want to express our gratitude to all the co-workers for their time, interest, and contribution towards this study.

FUNDING

This research received no external funding.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

SUPPLEMENTARY MATERIAL

Supplementary material associated with this article can be found, in the online version, at https://oss.jocpd.com/files/article/2049751994917109760/attachment/Supplementary%20material.docx.

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How to cite this article: Ling Xiao, Xi Zhao, Lin Ye, Dan Zhou. A prediction model for the long-term survival of primary molars after Vitapex pulpectomy. Journal of Clinical Pediatric Dentistry. 2026; 50(3): 222-232. doi: 10.22514/jocpd.2026.077.