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ORIGINAL RESEARCH

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Extraction versus pulpectomy for primary molar apical periodontitis: propensity-matched routine-care evidence on successor-tooth development

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Abstract

Background: The long-term successor-tooth consequences of extracting or retaining primary molars with apical/furcation disease remain uncertain. This study compared successor premolar outcomes after extraction versus pulpectomy in routine pediatric dental care. **Methods**: This two-center retrospective cohort included children aged 3–9 years treated in pediatric dental services in Tianjin, China (index treatment during 2016–2020), with follow-up from the index procedure until successor premolar eruption, transfer/loss to follow-up, orthodontic intervention, or study end in 2024. The tooth was the unit of analysis. Propensity score matching with exact matching on tooth type and arch produced 150 matched teeth per group. Primary inference used matched-set models with child-level cluster-robust variance. The primary outcome was any successor premolar abnormality: developmental stage difference $\geq$1 level, eruption delay $\geq$12 months, positional anomaly, or enamel developmental defect. Direct dental costs were analyzed as direct charges only. **Results**: Successor abnormalities occurred in 36.0% after extraction versus 24.0% after pulpectomy (absolute risk difference 12.0%, 95% confidence interval (CI) 1.7–22.3; odds ratio (OR) 1.78, 95% CI 1.08–2.94; p = 0.024), mainly reflecting eruption delay and positional anomalies. Space loss >2 mm was more common after extraction (37.1% *vs.* 4.8%; $p < 0.001$). The association was attenuated among extraction cases with timely, high-adherence space maintenance. Pulpectomy required more visits and higher direct charges. **Conclusions**: In this retrospective routine-care cohort, extraction was associated with a higher risk of the composite successor premolar abnormality than pulpectomy; the estimates should be interpreted as adjusted associations rather than causal effects. Treatment choice should be individualized according to restorability, root resorption, successor stage, feasibility of definitive restoration, and family burden, with timely sustained space maintenance prioritized when extraction is necessary.

Keywords

Apical periodontitis; Pulpectomy; Tooth extraction; Successor tooth development; Propensity score matching; Space maintenance

1. Introduction

Primary molar apical or furcation disease is common in childhood, and management decisions extend beyond short-term relief of pain and infection. The initial decision to extract or retain a diseased primary molar may influence arch integrity, eruption pathway, and development of the permanent successor premolar [1–3]. In everyday pediatric dental practice, clinicians therefore balance source control, restorability, root resorption, child cooperation, and family capacity for follow-up when choosing between extraction and pulpectomy [4, 5].

Guidance generally favors tooth retention when predictable infection control and a durable coronal seal can be achieved, but routine implementation is heterogeneous [4–6]. In this study, "routine-care" or "real-world" evidence refers to consecutive electronic records from two tertiary pediatric dental services, clinician/family-selected treatment rather than random assignment, variable operators and care settings, and follow-up imaging obtained during usual clinical care rather than protocol-mandated trial visits [7].

The remaining knowledge gap is specific. Previous studies have mainly evaluated short-term healing or survival of pulpectomized primary teeth [8–11]. Other studies have addressed radiographic effects of diseased primary molars on successors or space loss after premature extraction [1, 2, 12]. Direct comparisons of extraction versus pulpectomy with successor-centered endpoints, follow-up to eruption, explicit accounting for space maintenance and stainless-steel crown

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coverage, and adjustment for baseline treatment-selection factors remain limited [1, 2, 13]. This gap restricts the ability of clinicians to estimate downstream developmental risk associated with each management pathway.

Biologically, both disease and treatment pathways could affect the successor. Persistent infection may alter the follicular environment and eruption biology [14–17], whereas premature loss of a primary molar may reduce arch length, promote mesial drift or tipping of adjacent teeth, and redirect eruption [12, 18, 19]. We, therefore, hypothesized that extraction would be associated with a higher risk of successor premolar abnormalities than pulpectomy, particularly through eruption delay and positional disturbance, and that timely, adherent space maintenance would attenuate this association. The primary objective was to compare extraction with pulpectomy for primary first or second molars with apical/furcation disease using a clinically oriented composite successor endpoint. Secondary objectives were to quantify arch-space loss, pulpectomy failure, and direct healthcare utilization.

2. Materials and methods

2.1 Study design, setting, and reporting

This two-center retrospective cohort study was conducted in tertiary pediatric dental services in Tianjin, China: Tianjin Children's Hospital and Tianjin Stomatological Hospital. The study is reported in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) recommendations for cohort studies, and a completed reporting checklist is provided as **Supplementary material 1** [20]. Consecutive candidate records for index treatment during 2016–2020 were identified from institutional electronic medical records (EMR), billing systems, and picture archiving and communication systems, with follow-up through 2024 or censoring. The tooth was the unit of analysis. The center and child identifiers were retained for every record; center was included in the propensity-score model and adjusted analyses, and child-level clustering was addressed in primary and sensitivity models. The protocol was approved by the Ethics Committee of Tianjin Children's Hospital (W-2025-052), and informed consent was waived due to anonymized retrospective data.

2.2 Sample size and precision

No formal a priori sample-size calculation was performed because this retrospective study used all consecutive eligible records available in the prespecified accrual window. The matched analytic sample size was determined by common-support availability after exact matching on tooth type and arch; therefore, the matched cohort represents teeth for which both treatment strategies were clinically plausible, not the entire population of diseased primary molars. A *post hoc* precision assessment was reported: with 150 teeth per group, the observed 12.0 percentage-point difference in the primary composite endpoint had a 95% confidence interval (CI) of 1.7 to 22.3 percentage points, indicating the precision of the available routine-care estimate rather than prospective trial power.

2.3 Participants and eligibility criteria

Eligible participants were children aged 3–9 years with apical or furcation disease of a first or second primary molar, confirmed by concordant clinical findings and baseline radiographs on the index date. Tooth-level eligibility required an identifiable index primary molar, interpretable baseline imaging, a visible successor premolar germ, and sufficient documentation to determine the baseline root-resorption grade, lesion extent, restorability/caries burden, and successor developmental stage when visible. Radiographically, apical-only involvement was defined as radiolucency or periodontal-ligament widening localized to the root apex without interradicular radiolucency; furcation involvement was defined as interradicular radiolucency or trabecular bone loss between the roots; and furcation plus follicle involvement was defined as extension to, enlargement of, or disruption of the cortical border of the successor follicular space. Teeth were excluded if the apical diagnosis was uncertain, baseline imaging was non-interpretable, the successor tooth could not be assessed, congenital craniofacial anomalies were present, the index tooth had received definitive treatment within a 12-month look-back period, orthodontic treatment affected the index segment, or concurrent interventions were likely to alter eruption/space in the segment. Physiological root resorption was not ignored: it was graded as none, $<1/3$, 1/3–2/3, or $>2/3$ of root length and was included in the propensity model; teeth with imminent exfoliation or eruption documented at baseline were excluded from outcome assessment. Eligibility and exposure were ascertained using a prespecified hierarchy (procedure codes, operative/nursing records, and radiographic verification), with 10% of records re-abstracted by a second reviewer.

2.4 Exposure and treatment allocation

Exposure was the initial definitive treatment strategy, not a randomized assignment. In routine care, the treating pediatric dentist selected extraction or pulpectomy after clinical and radiographic assessment and discussion with the family. Pulpectomy was generally selected when the tooth was restorable, adequate coronal seal or stainless-steel crown placement was feasible, root resorption was compatible with retention, infection could be controlled, and exfoliation was not imminent [4, 5, 21]. Extraction was generally selected for non-restorable teeth, severe structural loss, extensive furcation or follicular involvement, pathologic mobility, advanced root resorption or imminent exfoliation, persistent acute infection requiring prompt source control, inability to obtain a durable restoration, or inability to ensure follow-up [4, 5]. Operator judgment, care setting, anesthesia/sedation requirements, and documented family preference were abstracted where available because these factors could influence allocation. These treatment-selection factors were harmonized across centers and incorporated as confounders or sensitivity variables. The extraction group included simple or surgical extraction performed in clinic, sedation suite, or theatre. The retention group included pulpectomy with canal instrumentation/irrigation/obturation followed by definitive restoration; teeth managed with lesion sterilization and tissue repair protocols were excluded from the primary analysis and evaluated in sensitivity analyses. Where avail-

able, technical factors (rubber dam use, irrigant/medicament, obturation material and radiographic quality, and stainless-steel crown placement) were abstracted and harmonized.

2.5 Co-interventions

Key co-interventions were space maintainers after extraction, classified by timing and adherence. "Timely/high-adherence" was defined as placement within 4 weeks and appliance-*in-situ* for ≥80% of observable follow-up days; "delayed/low-adherence" as later placement or <80%; and "none" as no appliance. The 4-week threshold reflected the local practice window for post-extraction appliance fabrication/insertion and the clinical concern that mesial drift may begin soon after premature molar loss; the ≥80% threshold was prespecified to distinguish sustained appliance use from intermittent or poorly documented use [18, 19, 22]. These thresholds were pragmatic clinical cut-points rather than biologic cut-points, and their interpretation was tested in sensitivity analyses. Adherence was calculated as appliance-days/observable follow-up days using clinic documentation and radiographic confirmation when needed. Sedation/anesthesia regimen, care setting, operator seniority, and calendar year were recorded as potential confounders.

2.6 Outcome definitions and assessment

The primary outcome was any abnormality of the successor premolar (tooth-level composite), determined from clinical records and radiographs by examiners blinded to the treatment strategy. The composite was selected because developmental delay, delayed eruption, positional disturbance, and enamel developmental defects may each trigger additional monitoring, restorative care, orthodontic assessment, or family concern after management of a diseased primary molar. However, the components do not have identical biologic mechanisms or clinical weight; therefore, each component was reported separately and interpreted descriptively. The composite was met if ≥1 prespecified component was present: (1) developmental stage difference ≥1 level using Demirjian or Nolla criteria, with the contralateral homonymous tooth as the reference when available or age-/sex-specific norms otherwise [23, 24]; (2) eruption delay ≥12 months compared with the contralateral tooth, documented eruption chronology, or radiographic/clinical expectation; (3) positional anomaly, defined as long-axis tilt >25°, mesiodistal offset >2 mm, or rotation >30°, including ectopic eruption; or (4) enamel developmental defect recorded after eruption using the Fédération Dentaire Internationale (FDI) Developmental Defects of Enamel (DDE) index [25].

Secondary outcomes included: (a) pulpectomy failure, defined as pain or sinus tract recurrence, radiographic lesion progression, retreatment, or extraction; (b) arch space loss adjacent to the index tooth, measured in millimeters and dichotomized as >2 mm; and (c) healthcare utilization, defined as the number of dental visits and direct dental costs in Chinese yuan (CNY) linked to the index tooth. Pulpectomy failure was summarized at 24 and 60 months (±3-month window); time-to-event analyses used the index date as time zero, with orthodontic intervention before eruption treated as a competing event. Healthcare utilization was obtained from visit records and billing ledgers, summed from the index date to successor eruption/censoring or study end, and analyzed as direct dental charges only; indirect family costs, travel costs, parental work loss, and non-dental medical charges were not included.

2.7 Radiographic measurement procedures

Radiographs (panoramic, bitewing, and periapical; cone-beam computed tomography (CBCT) when clinically indicated) were calibrated using embedded scales/metadata, and linear/angular measures were obtained with standardized digital caliper methods. Space loss was assessed radiographically as the change from baseline to the last evaluable follow-up image in the mesiodistal length of the index segment. For first primary molars, the reference interval was the distal surface of the primary canine to the mesial surface of the second primary molar; for second primary molars, it was the distal surface of the first primary molar to the mesial surface of the first permanent molar. When the baseline landmark was obscured by the index disease or extraction socket, the earliest interpretable post-treatment image was used and the reason was recorded. Measurements were performed on the same type of calibrated image whenever possible, repeated when image quality was borderline, and applied identically in extraction and pulpectomy groups. Two trained examiners blinded to treatment independently scored outcomes; disagreements or equivocal radiographic findings were adjudicated by a third examiner. Imaging quality criteria were applied at each time point, and non-interpretable studies were excluded for that time point with reasons recorded. Assessments were conducted at baseline, 6, 12, and 24 months, and annually thereafter until eruption or censoring; the last interpretable image before eruption (or study end) was used for final composite classification.

2.8 Data sources, follow-up and quality assurance

A retrospective dataset was assembled by linking EMR, billing/charge catalogs, and picture archiving and communication systems (PACS) across the two participating tertiary hospitals. EMR data included demographics, visit dates, care setting, operator seniority, medications and anesthesia notes, dental charting, family-reported appliance use, and clinical indications for extraction or retention. Billing records provided procedure identifiers, visit counts, material charges, radiography charges, anesthesia/sedation charges when linked to dental care, and direct costs for exposure and utilization classification. PACS supplied panoramic, bitewing, and periapical radiographs (CBCT when clinically indicated) with device metadata for scale calibration. Variables were harmonized using a standardized data dictionary before analysis.

2.9 Follow-up and time zero

Follow-up continued until successor premolar eruption, death, transfer outside the network, loss to follow-up, or study end (2024), with censoring reasons recorded. Orthodontic in-

terventions before spontaneous eruption were captured and treated as competing events in time-to-event analyses. The index date was the first definitive source-control procedure; for multi-visit pulpectomy, the obturation date was used because the tooth was not classified as definitively retained until root-canal filling was completed. This definition avoided incorrectly counting the interval between initial access and obturation as event-free pulpectomy follow-up. A sensitivity analysis using the first pulpectomy visit as time zero was performed and did not materially change the interpretation.

2.10 Examiner calibration and quality assurance

Before formal scoring, examiners completed a calibration session using training radiographs not included in the analytic dataset and discussed definitions for root-resorption grade, Nolla/Demirjian successor stage, eruption delay, positional anomaly, enamel defect, and space-loss landmarks. Calibration was accepted only after achieving $\kappa \geq 0.80$ for categorical measures and intraclass correlation coefficient (ICC) $\geq$0.90 for continuous measurements; observed post-calibration agreement was κ = 0.84 for root-resorption grade, κ = 0.86 for developmental stage category, κ = 0.88 for positional anomaly, and κ = 0.82 for enamel defects, with ICC = 0.94 for linear measurements and ICC = 0.92 for angular measurements. Reliability was then monitored by duplicate scoring of a random subset during the study. Only images meeting predefined quality criteria were scored; non-usable or equivocal studies were excluded or adjudicated with reasons logged. Measurements were performed on calibrated viewers using embedded scales/metadata. Two examiners blinded to treatment independently scored outcomes, with adjudication by a third examiner when needed. Data checks included range/logic rules, automated queries for outliers and date inconsistencies, and 10% random re-abstraction of key fields. All datasets were de-identified and stored on secure institutional servers with access controls and audit trails under local data-governance policies.

2.11 Statistical analysis

Analyses were prespecified and conducted at the tooth level. Covariates for the propensity-score model were selected a priori from a clinical causal framework rather than from statistical significance testing. The logistic propensity model incorporated demographics (age, sex, body mass index (BMI) *z*-score), center, index year, care setting, lesion severity (extent, sinus tract), root-resorption grade, restorability/caries burden (including stainless-steel crown (SSC) feasibility), baseline successor developmental stage when visible, crowding/space-risk, treatment setting, and operator seniority. Missing covariates were imputed using multiple imputation by chained equations (20 datasets) and combined using Rubin's rules [26]. Teeth were matched 1:1 without replacement using nearest-neighbor matching on the logit propensity score with a caliper of 0.20 standard deviation (SD), with exact matching on tooth type (first/second primary molar) and arch (maxilla/mandible) [27, 28]. Common support was assessed before matching; post-matching balance was evaluated using standardized mean differences (SMDs), with values <0.10 considered acceptable, and visually summarized in balance plots [29].

The primary comparison used conditional logistic regression with matched-set strata to estimate odds ratios (ORs) with 95% CIs, with cluster-robust variance at the child level to account for multiple teeth contributed by the same child. Absolute risk differences (ARDs) were calculated in the matched cohort, with adjusted ARDs obtained by marginal standardization in sensitivity analyses. Additional sensitivity analyses considered generalized estimating equations (GEE) with exchangeable correlation, mixed-effects logistic regression with a child-level random intercept, and a one-tooth-per-child analysis. Prespecified subgroup effects were explored using interaction terms and interpreted as exploratory.

For pulpectomy failure, Kaplan–Meier curves and Cox models with cluster-robust variance were used; competing events (*e.g.*, orthodontic intervention before eruption) were analyzed with Fine–Gray models [30]. In the full eligible cohort, inverse-probability-of-treatment weighting (IPTW) and overlap weighting were used as robustness checks, with post-weighting balance assessed by SMDs [31]. Sensitivity analyses evaluated alternative exposure definitions and restrictions (*e.g.*, pulpectomy only, pulpectomy with SSC, extraction with timely/high-adherence space maintenance), alternative matching specifications (caliper variation, trimming), and a one-tooth-per-child analysis. Model discrimination and calibration were interpreted using standard prediction-model performance principles [32]. Skewed utilization outcomes were summarized as median and interquartile range (IQR) and compared with Wilcoxon tests; categorical outcomes were compared with chi-square tests. Two-sided α = 0.05 was used for the primary comparison. Because component, subgroup, and secondary analyses were not adjusted for multiplicity, their p values were interpreted descriptively, with emphasis on effect sizes and 95% CIs. Analyses were performed in R version 4.3.2 and Stata/MP version 18.0 (StataCorp LLC, College Station, TX, USA).

3. Results

3.1 Baseline characteristics and covariate balance

A total of 1500 children aged 3–9 years with primary molar apical periodontitis or furcation disease (index treatment during 2016–2020) were identified from the two participating tertiary centers. After exclusions (incomplete diagnostic imaging, prior orthodontic treatment, congenital anomalies, diagnoses other than apical periodontitis (AP), or missing key covariates), 1080 children (1720 teeth) comprised the eligible cohort (Fig. 1). The extraction strategy included 840 teeth from 540 children, and the pulpectomy strategy included 880 teeth from 560 children; 20 children contributed teeth to both treatment strategies. Both centers contributed to both treatment groups, and center was retained in the propensity-score and adjusted models. Propensity score matching with exact matching on tooth type and arch yielded 150 matched teeth per group (Table 1, Fig. 1).

Before matching, the extraction group was younger (6.2 ±

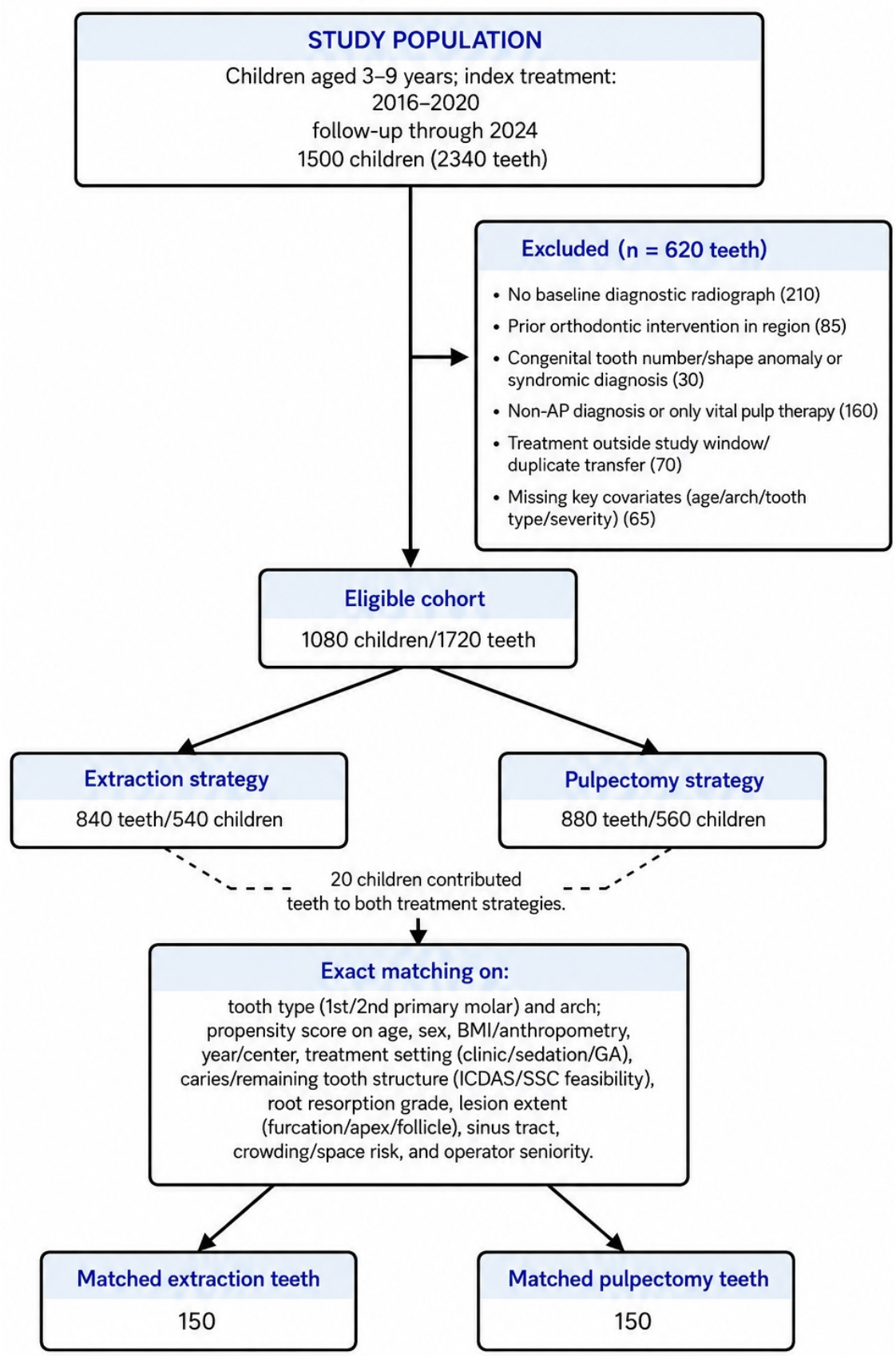


FIGURE 1. Study flow and matching. Of 1500 screened children with index treatment during 2016–2020, 1080 children (1720 teeth) were eligible; 840 teeth from 540 children received extraction and 880 teeth from 560 children received pulpectomy, with 20 children contributing teeth to both treatment strategies. Exact matching on tooth type/arch and propensity score matching produced 150 matched teeth per group; follow-up continued through 2024 or censoring. SSC, stainless-steel crown; AP, apical periodontitis; BMI, body mass index; GA, general anesthesia; ICDAS, International Caries Detection and Assessment System.

TABLE 1. Baseline characteristics before and after PSM.

Characteristic	Unmatched Extraction (n = 840)	Unmatched Pulpectomy (n = 880)	*p* value	SMD	PSM Extraction (n = 150)	PSM Pulpectomy (n = 150)	SMD
Age at index, yr, mean (SD)	6.2 (1.4)	6.6 (1.3)	<0.001	0.31	6.4 (1.3)	6.5 (1.3)	0.06
Male sex, n (%)	478 (56.9)	484 (55.0)	0.410	0.04	84 (56.0)	83 (55.3)	0.01
BMI *z*-score, mean (SD)	0.10 (0.90)	0.15 (0.88)	0.280	0.06	0.12 (0.89)	0.14 (0.87)	0.02
Primary molar type, n (%)							
First primary molar	294 (35.0)	484 (55.0)	<0.001	0.41	75 (50.0)	75 (50.0)	0.00
Second primary molar	546 (65.0)	396 (45.0)			75 (50.0)	75 (50.0)	0.00
Arch, n (%)							
Maxilla	336 (40.0)	440 (50.0)	<0.001	0.20	67 (44.7)	67 (44.7)	0.00
Mandible	504 (60.0)	440 (50.0)			83 (55.3)	83 (55.3)	0.00
Root resorption grade, n (%)							
None	126 (15.0)	264 (30.0)	<0.001	0.36	33 (22.0)	35 (23.3)	0.03
<1/3	210 (25.0)	308 (35.0)			45 (30.0)	47 (31.3)	0.03
1/3–2/3	294 (35.0)	220 (25.0)			49 (32.7)	48 (32.0)	0.02
>2/3	210 (25.0)	88 (10.0)			23 (15.3)	20 (13.3)	0.06
Lesion extent, n (%)							
Apical only	252 (30.0)	396 (45.0)	<0.001	0.31	57 (38.0)	59 (39.3)	0.03
Furcation involvement	420 (50.0)	352 (40.0)			68 (45.3)	66 (44.0)	0.03
Furcation + follicle involvement	168 (20.0)	132 (15.0)			25 (16.7)	25 (16.7)	0.00
Sinus tract present, n (%)	235 (28.0)	158 (18.0)	<0.001	0.24	33 (22.0)	32 (21.3)	0.02
Caries/remaining structure (ICDAS-based), n (%)							
Mild	84 (10.0)	176 (20.0)	<0.001	0.32	22 (14.7)	23 (15.3)	0.02
Moderate	294 (35.0)	396 (45.0)			68 (45.3)	69 (46.0)	0.01
Severe (limited restorability)	462 (55.0)	308 (35.0)			60 (40.0)	58 (38.7)	0.03
SSC feasible at baseline, n (%)	294 (35.0)	528 (60.0)	<0.001	0.52	78 (52.0)	81 (54.0)	0.04
Treatment setting, n (%)							
Clinic (no sedation)	672 (80.0)	572 (65.0)	<0.001	0.33	108 (72.0)	105 (70.0)	0.04
Conscious sedation	126 (15.0)	220 (25.0)			33 (22.0)	34 (22.7)	0.02
General anesthesia	42 (5.0)	88 (10.0)			9 (6.0)	11 (7.3)	0.05
Operator seniority, n (%)							
Resident/trainee	504 (60.0)	352 (40.0)	<0.001	0.41	72 (48.0)	69 (46.0)	0.04
Specialist/consultant	336 (40.0)	528 (60.0)			78 (52.0)	81 (54.0)	0.04
Crowding/space-loss risk, n (%)	294 (35.0)	264 (30.0)	0.030	0.10	48 (32.0)	47 (31.3)	0.01
Index treatment year, n (%)							
2016–2019	378 (45.0)	352 (40.0)	0.040	0.10	63 (42.0)	62 (41.3)	0.01
2020	462 (55.0)	528 (60.0)			87 (58.0)	88 (58.7)	0.01

SSC, stainless-steel crown; SMD, standardized mean difference; PSM, propensity score matching; SD, standard deviation; BMI, body mass index; ICDAS, International Caries Detection and Assessment System.

1.4 *vs.* 6.6 ± 1.3 years; $p < 0.001$) and had more severe disease and lower restorability, including fewer teeth suitable for stainless-steel crown coverage (35.0% *vs.* 60.0%), more outpatient procedures without sedation (80.0% *vs.* 65.0%), and greater resident involvement (60.0% *vs.* 40.0%) (Table 1). After matching, all measured covariates were well balanced (standardized mean differences <0.1), indicating improved comparability for measured baseline factors (Fig. 2). The 1420 unmatched teeth comprised 690 extraction and 730 pulpectomy teeth with limited common support; these teeth more often represented strong clinical indications for one strategy, such as non-restorable or advanced-resorption extraction cases and highly restorable, lower-severity pulpectomy cases. Therefore, the matched analysis estimates the association among teeth for which both strategies were clinically plausible, whereas the full eligible cohort was retained for IPTW and overlap-weighted robustness analyses.

Population and unit of analysis: Teeth from children aged 3–9 years treated during 2016–2020; analyses are at the tooth level with child-level factors attributed to teeth. Child-level clustering was addressed in primary modelling using robust standard errors and in sensitivity analyses using generalized estimating equations (GEE), mixed-effects, and one-tooth-per-child approaches. Groups: Extraction strategy *vs.* retain-tooth strategy (pulpectomy). Matching: Propensity scores estimated by logistic regression using a priori clinical covariates; exact match on primary molar type (first/second) and arch (maxilla/mandible); 1:1 nearest-neighbor matching without replacement with caliper 0.20 × SD (logit-PS). Balance diagnostics: Standardized mean difference (SMD) is reported; values <0.10 indicate good balance. *p* values are shown for unmatched comparisons; for matched samples, inferential *p* values are not emphasized in accordance with reporting guidance.

3.2 Primary composite outcome

In the propensity score–matched cohort, successor premolar abnormalities were more frequent after extraction than pulpectomy, occurring in 54/150 (36.0%) versus 36/150 (24.0%) teeth (Fig. 3). The absolute risk difference was 12.0 percentage points (95% CI 1.7–22.3) in favor of pulpectomy (Table 2). Wilson 95% CIs for group proportions are shown in Fig. 3, and estimates were based on the matched sample with exact matching on tooth type and arch (Fig. 3; Table 2).

The corresponding OR was 1.78 (95% CI 1.08–2.94; $p = 0.024$) comparing extraction with pulpectomy (Table 2). Counts and interval estimates in Fig. 3 align with those in Table 2 and were derived from the same matched cohort (Fig. 3; Table 2).

Analyses are based on the propensity score–matched sample (n = 150 per group) with exact matching on tooth type (first/second primary molar) and arch (maxilla/mandible). ARD is expressed as percentage points (extraction minus pulpectomy). The primary OR, 95% CI, and *p* value were

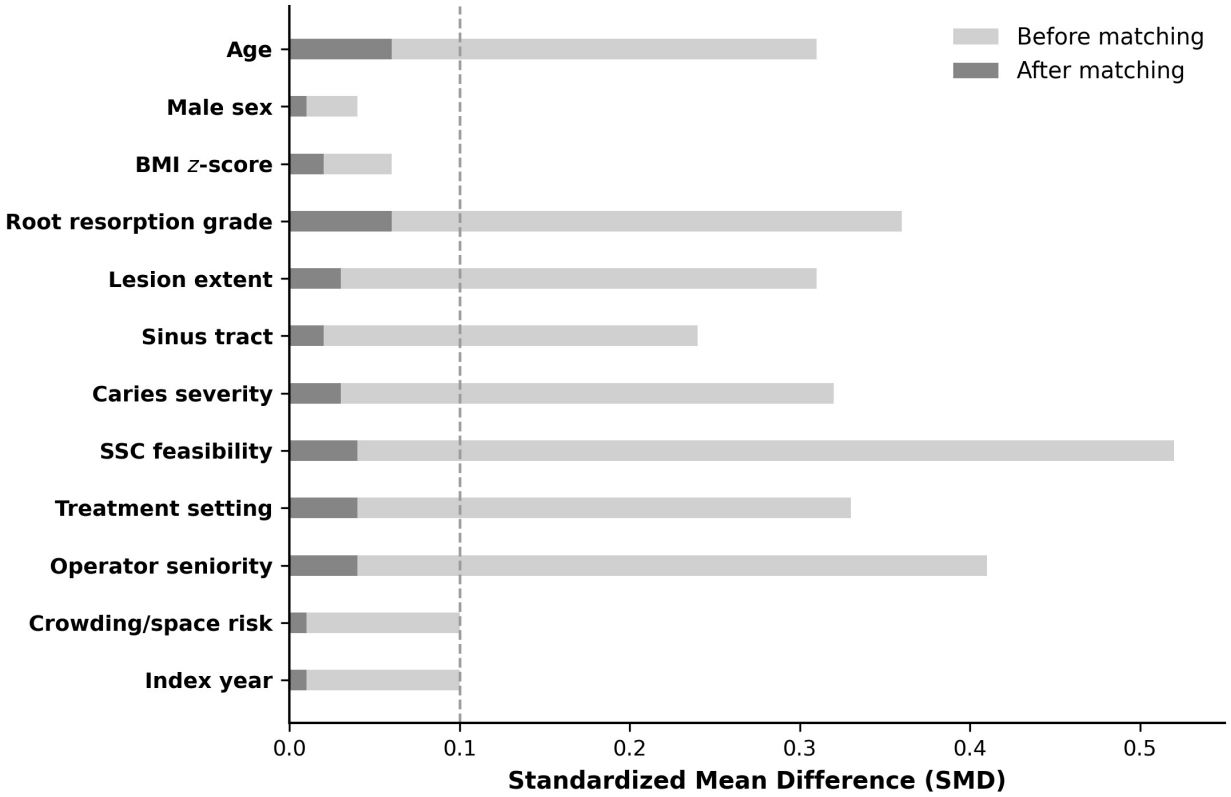


FIGURE 2. Covariate balance before and after propensity score matching (PSM). Standardized mean differences (SMDs) for baseline covariates comparing extraction and pulpectomy groups are shown before and after matching; the dashed line marks the prespecified balance threshold (SMD = 0.1). The propensity model included demographic, center, index-year, lesion-severity, root-resorption, restorability, successor-stage, care-setting, operator-seniority, and space-risk covariates. All displayed covariates were adequately balanced after matching. SSC, stainless-steel crown; BMI, body mass index.

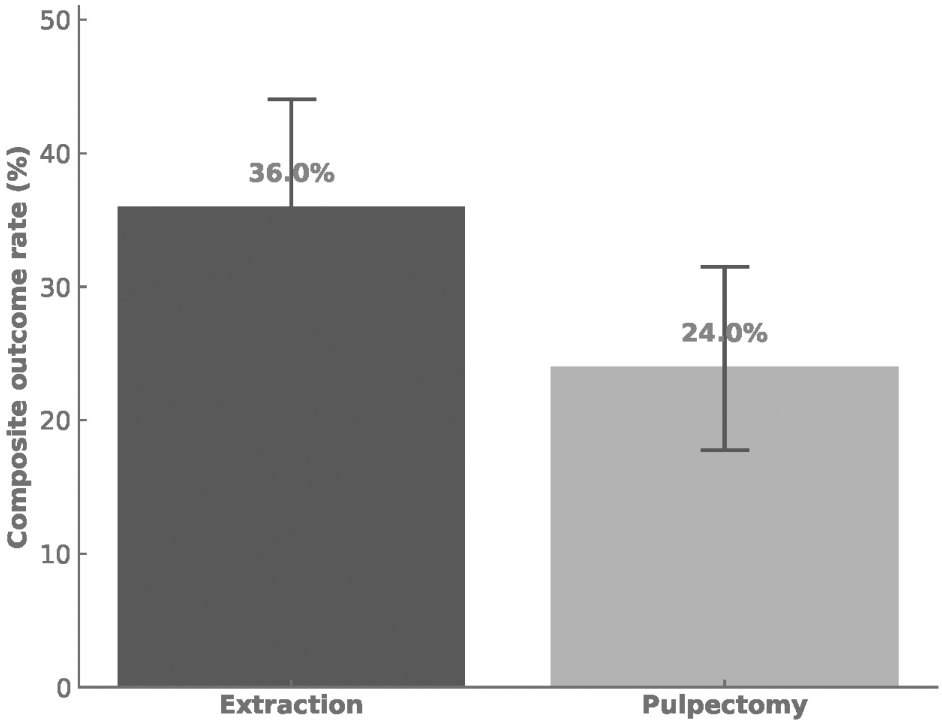


FIGURE 3. Composite abnormality of the successor tooth after extraction versus pulpectomy (matched cohort). Bars show the proportion with any successor abnormality in the propensity score–matched cohort (n = 150 per group); error bars indicate Wilson 95% CIs. The composite included ≥1 of: developmental stage difference ≥1 level, eruption delay ≥12 months, positional anomaly, or enamel developmental defect. The inferential OR was estimated using a matched-set model with child-level cluster-robust variance.

TABLE 2. Comparison of the primary composite outcome in the propensity score–matched cohort.

Outcome (per tooth)	Extraction n/N (%)	Pulpectomy n/N (%)	ARD, % (95% CI)	OR (95% CI)	*p* value
Any abnormality of successor tooth (composite)	54/150 (36.0)	36/150 (24.0)	12.0 (1.7 to 22.3)	1.78 (1.08 to 2.94)	0.024

ARD, absolute risk difference; CI, confidence interval; OR, odds ratio.

estimated using conditional logistic regression with matched-set strata and child-level cluster-robust variance. The 95% CI for ARD is presented for clinical interpretation of the absolute effect size. The composite endpoint was counted if any of the following was present: developmental stage difference ≥1 (Demirjian/Nolla), eruption delay ≥12 months, positional anomaly (tilt >25°, offset >2 mm, or rotation >30°, including ectopic eruption), or enamel developmental defect (FDI DDE).

3.3 Component analysis of the composite endpoint

In the matched cohort, component frequencies were assessed per tooth for extraction versus pulpectomy (Fig. 4; Table 3). Developmental stage difference ≥1 level occurred in 12.0% versus 10.0%; eruption delay ≥12 months in 15.3% versus 9.3%; positional anomaly in 18.0% versus 11.3%; and enamel developmental defects in 8.0% versus 6.0% (Fig. 4; Table 3). Because components were not mutually exclusive, their percentages exceeded the overall composite rate (Fig. 4; Table 3).

Absolute risk differences generally favored pulpectomy but were imprecise: 2.0 percentage points for stage difference (95% CI −5.08 to 9.08), 6.0 for eruption delay (95% CI −1.41 to 13.41), 6.7 for positional anomaly (95% CI −1.30 to 14.64), and 2.0 for enamel defects (95% CI −3.77 to 7.77) (Table 3). Between-group *p* values were 0.580, 0.114, 0.103, and 0.497, respectively (Table 3). None of the individual components reached statistical significance; therefore, component analyses were interpreted as descriptive support for the composite pattern rather than evidence of component-specific effects.

Analyses are based on the propensity score–matched sample (n = 150 per group) with exact matching on tooth type (first/second primary molar) and arch (maxilla/mandible). ARD is expressed as percentage points (extraction minus pulpectomy). CIs for ARD were estimated for descriptive interpretation of component effect sizes; two-sided *p* values were obtained from component-level models and were not adjusted for multiplicity. Component categories are not mutually exclusive, therefore percentages do not sum to the composite endpoint. Because components differ in biologic mechanism and clinical weight, component analyses were interpreted descriptively. The operational thresholds were prespecified: developmental stage difference ≥1 level;

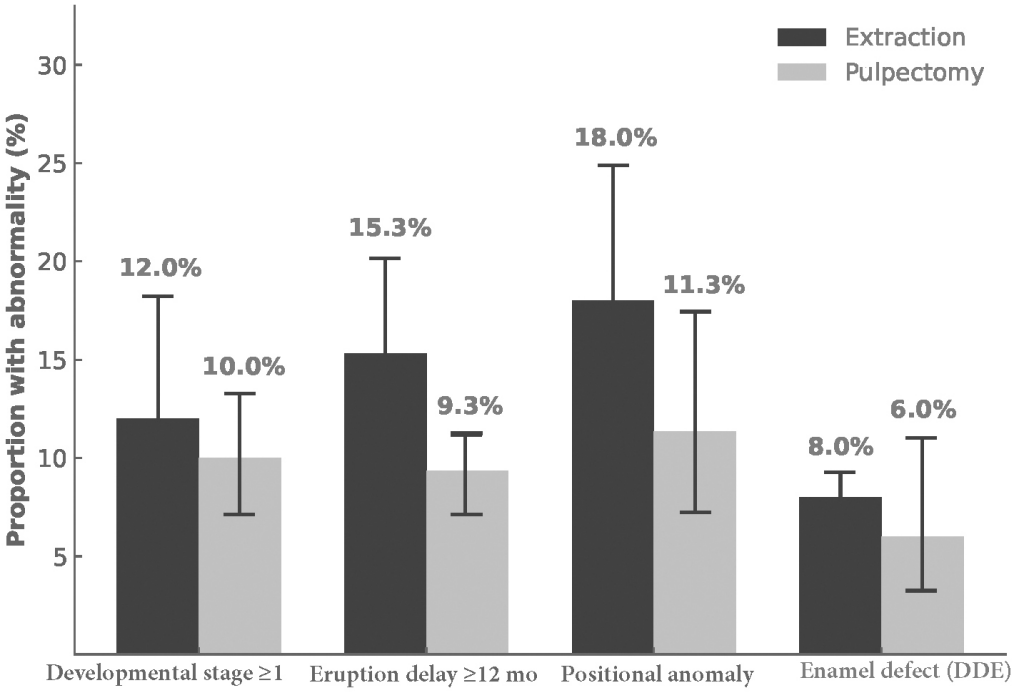


FIGURE 4. Component breakdown of the composite endpoint in the matched cohort. Grouped bars show the proportions (Wilson 95% CIs) of each successor abnormality by treatment group (n = 150/group). Components were developmental stage difference, eruption delay ≥12 months, positional anomaly, and enamel developmental defect. Components were not mutually exclusive and were interpreted descriptively because component-level analyses were not adjusted for multiplicity and individual component estimates were imprecise. DDE, Developmental Defects of Enamel.

TABLE 3. Component-by-component comparison of the composite endpoint in the propensity score–matched cohort.

Component (per tooth)	Extraction n/N (%)	Pulpectomy n/N (%)	ARD, % (95% CI)	*p* value
Developmental stage ≥1 (Demirjian/Nolla)	18/150 (12.0)	15/150 (10.0)	2.0 (−5.08 to 9.08)	0.580
Eruption delay ≥12 months	23/150 (15.3)	14/150 (9.3)	6.0 (−1.41 to 13.41)	0.114
Positional anomaly (tilt >25°, offset >2 mm, rotation >30°, including ectopic)	27/150 (18.0)	17/150 (11.3)	6.7 (−1.30 to 14.64)	0.103
Enamel developmental defect (FDI DDE)	12/150 (8.0)	9/150 (6.0)	2.0 (−3.77 to 7.77)	0.497

ARD, absolute risk difference; CI, confidence interval; DDE, Developmental Defects of Enamel; FDI, Fédération Dentaire Internationale.

eruption delay ≥12 months; positional anomaly defined by tilt >25°, offset >2 mm, or rotation >30° including ectopic eruption; enamel defect per FDI DDE criteria.

3.4 Multimodel regression for the primary composite endpoint

In the propensity score–matched cohort, extraction was consistently associated with higher odds of successor premolar abnormality than pulpectomy across prespecified logistic models (**Supplementary Table 1**). In the unadjusted model, the OR was 1.78 (95% CI 1.08–2.94; $p = 0.024$). After adjustment for demographics and center/index year, the OR was 1.74 (95% CI 1.05–2.89; $p = 0.031$), and after further adjustment for clinical and treatment-related covariates (root resorption, lesion extent, restorability/International Caries Detection and Assessment System (ICDAS) and stainless-steel crown feasibility, setting, operator seniority, and crowding/space risk), the OR was 1.69 (95% CI 1.01–2.84; $p = 0.045$) (**Supplementary Fig. 1**; **Supplementary Table 1**). Estimates were derived per tooth in the matched sample (150 teeth per group) with exact matching on tooth type and arch (**Supplementary Fig. 1**; **Supplementary Table 1**).

Model discrimination improved with additional covariates (area under the receiver operating characteristic curve (AUC) 0.58, 0.62, and 0.69), and calibration was acceptable (Hosmer–Lemeshow $p = 0.65$, 0.54, and 0.41) (**Supplementary Fig. 1**; **Supplementary Table 1**). Because the number of composite events was modest, fully adjusted regression was interpreted as supportive and potentially susceptible to overfitting; the main emphasis was placed on the matched effect size and its CI.

Sensitivity analyses that explicitly modelled within-child correlation (GEE, mixed-effects modelling, and one-tooth-per-child sampling) did not materially change the direction of the primary association; these analyses were treated as robustness checks rather than separate confirmatory tests.

3.5 Secondary outcomes: space management, treatment failure, and healthcare utilization

In the matched cohort, pulpectomy failure increased over time among teeth with evaluable follow-up: cumulative failure was 13.0% at 24 months (18/138) and 23.2% at 60 months (26/112), with Wilson 95% CIs shown in **Supplementary Fig. 2**. The reduction in evaluable denominators from 24 to 60 months reflected successor eruption, administrative censoring before 60 months, transfer/loss to follow-up, and non-interpretable follow-up imaging; censored teeth were not counted as failures. Space outcomes differed markedly by strategy. Space loss >2 mm occurred in 37.1% after extraction versus 4.8% after pulpectomy (ARD 32.3 percentage points, 95% CI 23.6–41.0; $p < 0.001$) (**Supplementary Table 2**).

Healthcare utilization was higher after pulpectomy (**Supplementary Table 2**), but this was interpreted as a descriptive utilization outcome rather than a formal cost-effectiveness analysis. Median visits per tooth were 3 (IQR 2–4; n = 150) after pulpectomy versus 2 (IQR 1–3; n = 148) after extraction ($p < 0.001$). Median direct costs were 1950 CNY (IQR 1450–2700; n = 147) after pulpectomy versus 1350 CNY (IQR 900–2100; n = 142) after extraction ($p < 0.001$) (**Supplementary Table 2**). Outcome-specific denominators reflect record availability (**Supplementary Table 2**).

3.6 Robustness across sensitivity and weighting analyses

Prespecified sensitivity analyses were directionally consistent with the primary propensity score–matched comparison (**Supplementary Table 3**; **Supplementary Fig. 3**). The primary analysis showed an ARD of 12.0% (95% CI 1.7–22.3) and an OR of 1.78 (95% CI 1.08–2.94; $p = 0.024$) (**Supplementary Table 3**; **Supplementary Fig. 3**). Restricting the retention group to pulpectomy only produced similar estimates (ARD 11.8%, 95% CI 1.4–22.2; OR 1.76, 95% CI 1.06–2.91; $p = 0.031$). In the retention-with-SSC subset, estimates were larger but less precise (ARD 14.2%, 95% CI 0.8–27.6; OR 2.05, 95% CI 0.99–3.80; $p = 0.052$), whereas in extraction cases with timely, high-adherence space maintenance, the association was attenuated (ARD 3.8%, 95% CI -12.8 to 20.4; OR 1.45, 95% CI 0.86–2.46; $p = 0.160$). Alternative matching specifications yielded comparable results, and propensity-score trimming produced modest attenuation (**Supplementary Table 3**; **Supplementary Fig. 3**).

In analyses of the full eligible cohort, inverse probability and overlap weighting also supported the overall pattern, with smaller effect sizes: IPTW OR 1.62 (95% CI 1.10–2.62) and ARD 9.7% (95% CI 2.3–17.1; $p = 0.015$), and overlap-weighted OR 1.58 (95% CI 1.06–2.55) and ARD 8.9% (95% CI 1.6–16.2; $p = 0.021$) (**Supplementary Table 3**; **Supplementary Fig. 3**). Across specifications, point estimates remained on the same side of the null and were broadly compatible with the primary matched analysis (**Supplementary Table 3**; **Supplementary Fig. 3**).

The consistency between matched and weighted analyses suggests that the main finding was not solely an artifact of matching; however, the smaller weighted estimates also indicate that the matched cohort may represent a narrower common-support population than the full eligible sample.

4. Discussion

This study provides an adjusted routine-care comparison of extraction versus pulpectomy for primary molars with apical/furcation disease. In the propensity score–matched cohort, extraction was associated with a higher probability of the prespecified composite successor abnormality than pulpectomy (ARD 12.0 percentage points; OR 1.78). This result should not be interpreted as proof that extraction causes successor abnormality because treatment was selected by clinicians and families, and residual confounding by indication remains plausible even after matching. In addition, none of the individual components reached statistical significance; their point estimates were directionally consistent but imprecise. The clinically relevant signal was driven mainly by eruption timing and position rather than enamel defects or developmental staging.

The findings complement current guidance that prioritizes retention when predictable source control and durable coronal coverage can be achieved [4–6], and they extend previous evidence by quantifying successor-focused endpoints under routine clinical conditions [1–3]. The routine-care designation is important because the dataset included consecutive records from two tertiary services, clinician/family-selected treatment, variation in operators, treatment settings, restorations, sedation, and space-maintainer use, and follow-up imaging obtained as part of usual care rather than a trial schedule [7]. The novelty is, therefore, not the general observation that premature extraction can produce space loss; rather, it is the matched tooth-level estimate of successor premolar abnormalities after two common clinical strategies, while considering tooth type, arch, root resorption, restorability, lesion extent, treatment setting, operator seniority, and space-maintainer adherence. Conversely, extraction without timely and adherent space maintenance predisposes to space loss, mesial drift and tilt, which can delay or redirect eruption [12, 13, 33]. The present data align with these mechanisms. Space loss greater than two millimeters was more frequent after extraction than after pulpectomy, and within the extraction pathway, the association with successor abnormality was attenuated among extraction cases with timely, high-adherence space maintenance [19, 22, 34], suggesting that high-quality space management may be a modifiable lever. However, adherence may also reflect family engagement, access, and follow-up capacity, so it should not be interpreted as a purely appliance-mediated effect.

The study also characterizes relevant clinical-economic trade-offs. Pulpectomy required more visits and incurred higher direct costs at the tooth level. These utilization differences are not trivial for families and systems, but direct cost alone should not be interpreted as evidence of inferior value [35]. If pulpectomy reduces clinically relevant successor abnormalities or future orthodontic burden in selected teeth, its higher short-term cost may be justified. Therefore, the cost analysis is descriptive and should be interpreted alongside effectiveness, adverse outcomes, feasibility of high-quality

pulpectomy, and the family's capacity for repeated visits.

Important limitations remain. First, the retrospective design relies on clinical records and imaging obtained for routine care; therefore, information bias is possible because documentation, evaluable imaging, and follow-up duration were not identical across groups. Second, confounding by indication cannot be eliminated: teeth selected for extraction had worse prognosis before matching, including more severe disease and lower restorability, and unmeasured factors such as parental preference, oral hygiene, operator judgment, and undocumented inflammation severity may still have influenced outcomes. Third, matching reduced the analytic cohort from 1720 eligible teeth to 300 matched teeth. This improved covariate balance but selected a common-support population and may reduce statistical power, exclude clinically extreme cases, and limit external validity. Fourth, multiple teeth from the same child may be correlated; primary models used child-clustered robust variance and sensitivity analyses considered GEE, mixed-effects, and one-tooth-per-child approaches, but residual within-child confounding remains possible. Fifth, the obturation date was used as time zero for multi-visit pulpectomy to reduce immortal-time bias, but alternative definitions may affect follow-up time. Sixth, space-maintainer adherence may partly reflect family engagement and access to care. Seventh, the composite endpoint blends components with different clinical weights, and the individual component estimates were imprecise. Finally, component, subgroup, and secondary analyses were not adjusted for multiplicity and should be interpreted descriptively. External validity primarily pertains to tertiary pediatric dental services in China and should be examined in community clinics and other health systems.

Taken together, these results provide decision-relevant but observational estimates grounded in routine practice. They support individualized treatment selection rather than a universal preference for either strategy. Retention is favored when restorability, root-resorption stage, successor developmental stage, infection control, and definitive coronal coverage make pulpectomy predictable. When extraction is necessary, the data identify timely and sustained space maintenance as an important risk-management measure. Future prospective studies with standardized treatment indications, imaging intervals, examiner calibration, adherence measurement, and formal cost-effectiveness methods are needed to confirm these observations.

5. Conclusions

In this retrospective routine-care cohort, extraction of infected primary molars was associated with a higher risk of the composite successor premolar abnormality than pulpectomy (ARD approximately 12%), mainly reflected by eruption delay and positional anomalies. The individual components were imprecise and did not reach statistical significance, and the findings should be interpreted as adjusted associations rather than causal effects. Timely, adherent space maintenance appeared to attenuate the excess risk after extraction, while definitive coronal coverage supported pulpectomy success. Pulpectomy required more visits and higher direct charges, but these costs should be weighed against potential developmental and orthodontic consequences rather than interpreted in isolation. Treatment should be individualized: retain restorable teeth when durable source control and coronal coverage are feasible, and prioritize timely sustained space maintenance when extraction is necessary.

AVAILABILITY OF DATA AND MATERIALS

The de-identified analytical dataset, data dictionary, and statistical code used in the current study are available from the corresponding author on reasonable request, subject to institutional ethics approval and data-governance restrictions.

AUTHOR CONTRIBUTIONS

XL, YRZ—conceptualization; data curation; methodology; software; validation; visualization. XL, YRZ, PD—formal analysis; resources. XL—funding acquisition; project administration; writing–review & editing. XL, YRZ, WJX—investigation; supervision. YRZ—writing–original draft. All authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The current study was approved by the Ethics Committee of Tianjin Children's Hospital (approval number W-2025-052). Due to the retrospective design and anonymized data, written informed consent was waived by the Ethics Committee.

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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/2117531963793260544/attachment/Supplementary%20material.docx.

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