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Research Article

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Gingivitis occurrence and risk factors in adolescent orthodontic patients: a retrospective cohort study

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Abstract

Objectives To identify factors associated with gingivitis and develop a risk prediction model in adolescent orthodontic patients.

Materials and Methods This retrospective cohort included 580 orthodontic patients aged 10–16 years. Time to first gingivitis was analyzed using Cox regression and Boruta feature selection. Discrimination, calibration, and clinical net benefit were assessed.

Results During a median follow-up of 16 months (interquartile range, 10–22 months), 319 patients (55.0%) developed gingivitis. Multivariable analysis showed that orthodontic auxiliary use, a positive anxiety screen, and grade III increased overjet were associated with a higher hazard of gingivitis, with adjusted hazard ratios (95% confidence intervals) of 1.56 (1.18–2.06), 1.43 (1.09–1.89), and 1.65 (1.05–2.60), respectively. The final model included five predictors: daily toothbrushing frequency, mandibular plane–sella–nasion angle (MP–SN), Frankfort–mandibular plane angle (FMA), anxiety status, and overjet. The apparent concordance index was 0.677. Apparent time-dependent areas under the receiver operating characteristic curve at 12, 24, and 36 months were 0.723, 0.716, and 0.857, respectively; corresponding Brier scores were 0.032, 0.048, and 0.063.

Conclusions Oral hygiene behavior, anxiety, and craniofacial morphology may inform gingivitis risk assessment. The model showed moderate apparent discrimination and requires internal and external validation.

Clinical Relevance The identified factors may help target oral hygiene support and periodontal monitoring during adolescent orthodontic treatment.

Keywords Gingivitis; Orthodontic treatment; Adolescents; Risk factors; Prediction model; Cox regression

1 Introduction

Malocclusion encompasses a diverse group of abnormalities arising from disharmonious relationships among the teeth, jaws, and craniofacial structures. The World Health Organization has designated it as one of the three major oral diseases of the 21st century [1]. A meta-analysis estimated the global prevalence of malocclusion among children and adolescents at 56%, with regional estimates of 81% in Africa, 71% in Europe, 53% in the Americas, and 48% in Asia. Although standardized epidemiological assessment criteria remain unavailable, meta-analytic evidence suggests an increasing prevalence worldwide [2, 3].

Orthodontic treatment is the primary approach to correcting malocclusion. However, multiple treatment-related factors can promote plaque accumulation and gingival inflammation, which manifests as redness, swelling, and bleeding. These changes may damage periodontal tissues and, in severe cases, compromise treatment success [4]. Early symptoms of gingivitis are subtle, with bleeding on probing and gingival redness becoming apparent as early lesions develop. Gingivitis is generally painless and rarely causes spontaneous bleeding, so many patients fail to recognize it [5].

Although gingivitis is common [6], its prevalence differs between orthodontic patients and the general population. Reported rates exceed 30% in the general population and may exceed 50% during orthodontic treatment [7]. Early risk prediction and intervention may help maintain oral health during treatment [8, 9]. Gingivitis may reflect oral hygiene behaviors, psychological status, orthodontic appliances, and craniofacial morphology. However, previous studies have predominantly used cross-sectional designs and focused on traditional oral hygiene factors, such as toothbrushing frequency and dental floss use [10]. Integrated prediction incorporating psychological factors, appliance types, orthodontic auxiliaries, and craniofacial measurements has received less attention. Conventional binary analyses at a single observation point cannot adequately account for differences in follow-up duration, event timing, and censoring. Individualized time-to-event prediction remains limited for adolescent orthodontic patients. This study examined first gingivitis occurrence from treatment initiation, with follow-up ending at diagnosis or the last evaluable visit. Candidate predictors included oral hygiene behaviors, psychological status, orthodontic treatment characteristics, and craniofacial measurements. A Cox proportional hazards model was developed to estimate individual risk at different follow-up times and inform early risk stratification and targeted prevention.

2 Materials and methods

2.1 Study design and ethical statement

This retrospective cohort study was designed and conducted in accordance with the World Medical Association Declaration of Helsinki, and was approved by the Ethics Committee of Union Hospital, Tongji Medical College, Huazhong University of Science and Technology (project number: KQHL20260704). All potential participants or their guardians received detailed explanations of the study objectives and methods. They then provided written informed consent for the anonymous use of their medical records.

2.2 Study population

Adolescent patients who initiated orthodontic treatment at Union Hospital, Tongji Medical College, Huazhong University of Science and Technology between January 2023 and December 2025 were eligible. Follow-up began at the initiation of orthodontic treatment, and longitudinal follow-up data were obtained from electronic medical records, oral examination records, and orthodontic follow-up records. The outcome was the first clinical diagnosis of gingivitis during follow-up. For patients who developed gingivitis, the event time was the interval between treatment initiation and the first diagnosis. Patients who remained free of gingivitis were followed until orthodontic treatment completion, the last evaluable follow-up visit, or the study cutoff date. A total of 580 patients were included, comprising 246 males and 334 females. Their ages ranged from 10 to 16 years (mean, 14.0 ± 1.0 years).

The inclusion criteria were as follows: (1) age of 10–16 years at orthodontic treatment initiation; (2) normal cognitive and communication abilities, allowing cooperation with oral examinations and questionnaire completion; (3) complete medical and follow-up records, including the treatment initiation date, baseline periodontal examination and intraoral photographs, treatment plan and appliance information, dates of all follow-up visits and corresponding gingival findings, and the first gingivitis diagnosis date or last evaluable follow-up date; (4) healthy periodontal tissues at treatment initiation, with no gingival redness, swelling, enlargement, bleeding on probing, or other inflammatory signs on baseline examination and pretreatment intraoral photographs; (5) at least one evaluable periodontal follow-up record after treatment initiation and a follow-up duration of at least 2 months; and (6) complete eruption of all first permanent molars.

The exclusion criteria were as follows: (1) unerupted permanent teeth; (2) a history of periodontal or oral mucosal disease; (3) antimicrobial use within the preceding month; (4) coexisting hypertension, diabetes, hematological disease, or immune system disease; and (5) inability to cooperate with examinations despite behavioral and psychological guidance.

2.3 Clinical examination and questionnaire

Clinical examinations were performed on site during follow-up. All oral examinations were conducted with patients in the supine position under LED surgical lighting. Qualified examiners used standard oral examination instruments and followed strict hospital infection control procedures. Examination supplies included disposable protective goggles, disposable mouth mirrors, disposable dental probes, and metal World Health Organization Community Periodontal Index (WHO CPI) probes.

Before follow-up began, participants and their parents completed a structured questionnaire. At the time of questionnaire completion, an oral examination confirmed that all participants had healthy periodontal tissues and no signs of gingivitis. Follow-up commenced after questionnaire completion, with the first occurrence of gingivitis during follow-up serving as the outcome. This sequence ensured that all candidate predictors were measured before the outcome occurred.

The questionnaire comprised four sections. The first covered sociodemographic characteristics, including baseline age, sex, and educational attainment. The second assessed oral health behaviors, including daily

toothbrushing frequency, dental floss or interdental brush use, and toothbrush type. The third assessed environmental tobacco smoke exposure, measured as the frequency of smoking at home by parents or other household members. The fourth evaluated baseline anxiety and depressive symptoms using the Hospital Anxiety and Depression Scale (HADS). The HADS contains 14 items divided equally between the anxiety subscale (HADS-A) and the depression subscale (HADS-D). Each item is scored from 0 to 3, giving each subscale a total score of 0–21. Higher scores indicate more severe symptoms on the corresponding subscale. Based on screening thresholds recommended in previous studies, HADS-A and HADS-D scores ≥8 defined positive anxiety and depression screens, respectively [11, 12]. Scores of 0–7 indicated a negative screen, 8–10 a borderline positive screen, and 11–21 a definite positive screen.

2.4 Oral examination

Gingivitis was screened using the Gingival Index (GI) and was defined as a GI score of 2 or 3, with bleeding on probing. Probing was combined with visual inspection. The CPI probe was gently inserted into the gingival sulcus, parallel to the tooth's long axis, with its tip directed toward the root. The entire sulcus was examined using short vertical probing movements. The presence of subgingival calculus was recorded based on tactile findings [13]. Other potential risk factors for gingivitis were also assessed, including maxillary and mandibular archwire dimensions, use of orthodontic auxiliaries (bands, transpalatal arches [TPAs], Nance appliances, power chains, etc.), hook positions and number, appliance type, overbite, overjet, and dental crowding. All examiners received standardized clinical training at the beginning of the epidemiological investigation.

Before the main investigation, a periodontist provided standardized training and calibration for two examiners. Fifty adolescents were randomly selected for calibration. Both examiners independently performed the initial examinations using the same gingival examination protocol and were blinded to each other's findings. After 30 days, both examiners repeated the examinations in the same participants. Agreement in gingivitis classification was assessed using kappa coefficients. The interexaminer kappa coefficient was 0.86 (95% confidence interval [CI], 0.76–0.96). Intraexaminer kappa values were 0.89 (95% CI, 0.80–0.98) and 0.91 (95% CI, 0.83–0.99) for examiners 1 and 2, respectively. These results indicated good interexaminer and intraexaminer agreement.

2.5 Maxillofacial morphological analysis

Craniofacial morphology was assessed using lateral cephalometric radiographs obtained within 1 month before orthodontic treatment initiation. All images preceded the start of gingivitis outcome observation. Images were acquired using a standardized protocol, with patients in a natural head position, maximum intercuspation, and a relaxed lip posture. When multiple pretreatment images were available, the image closest to treatment initiation that met the required measurement quality was selected as the baseline image.

Digital landmark identification and cephalometric measurements were performed using CliniView software (version 11.9). Measurements included sella–nasion–A point angle (SNA), sella–nasion–B point angle (SNB), A point–nasion–B point angle (ANB), mandibular plane–sella–nasion angle (MP–SN), Frankfort–mandibular plane angle (FMA), and facial angle. MP–SN was defined as the angle between the SN plane and the mandibular plane (Go–Gn). It represents mandibular plane inclination relative to the anterior cranial base. FMA

was defined as the angle between the Frankfort horizontal plane (Po–Or) and the mandibular plane. It was used to assess the vertical craniofacial growth pattern.

Two orthodontists with at least 2 years of cephalometric experience independently identified landmarks and performed all measurements. Both were blinded to questionnaire data and gingivitis outcomes to reduce observer bias. The mean of the two measurements was used for statistical analysis. If the difference between measurements exceeded the prespecified tolerance (>2° for angular measurements), a third senior orthodontist reviewed the measurements and determined the final value.

To assess reproducibility, 50 baseline lateral cephalometric radiographs were randomly selected. Both observers repeated landmark identification and measurements after 10 days without access to their initial results. Agreement was assessed using intraclass correlation coefficients (ICCs) and their 95% CIs. All interobserver and intraobserver ICCs exceeded 0.90, indicating good measurement agreement.

2.6 Statistical analysis

Continuous variables were summarized as means ± standard deviations (SDs) for normally distributed data or medians and interquartile ranges (IQRs) for nonnormally distributed data. Categorical variables were summarized as counts and percentages. Normality was assessed using the Kolmogorov–Smirnov test. Between-group comparisons used Student's t test for normally distributed variables and the Mann–Whitney U test for skewed variables. Categorical variables were compared using the chi-square test. Fisher's exact test was used when any expected cell frequency was <5.

Univariable and multivariable Cox proportional hazards regression models were used to examine associations between candidate variables and time to gingivitis onset. Results were expressed as hazard ratios (HRs) with 95% CIs. Variables with $P < 0.05$ in univariable analyses entered the initial multivariable model, followed by backward stepwise selection. The Boruta algorithm provided complementary identification of important features. Final candidate predictors were selected from the intersection of Boruta-confirmed variables and variables retained in the multivariable Cox model. Discrimination was assessed using the concordance index (C-index) and time-dependent areas under the receiver operating characteristic curve (AUCs) at 12, 24, and 36 months. Calibration was assessed using calibration curves and Brier scores. Clinical utility was evaluated using decision-curve analysis (DCA). No bootstrapping or cross-validation was performed; therefore, all reported model performance estimates represent apparent performance. All statistical analyses were conducted using R software, with a two-sided $P < 0.05$ considered statistically significant.

3 Results

3.1 Study population, follow-up, and outcome events

A total of 580 adolescents undergoing orthodontic treatment were included. During follow-up, 319 patients developed gingivitis, corresponding to an event proportion of 55.0%, whereas 261 remained free of gingivitis throughout follow-up. The median follow-up duration was 16 months (IQR, 10–22 months). The study

population comprised 246 male and 334 female patients, among whom 150 and 169 events occurred, respectively. The median age was 13.0 years (IQR, 12.0–14.0 years).

Compared with patients who did not develop gingivitis, those who developed gingivitis had longer observation periods, higher MP–SN, FMA, ANB, and facial angle values, and lower SNB values. The groups also differed in several oral hygiene behaviors, orthodontic treatment characteristics, anxiety and depression screening status, overjet, and dental crowding. Complete baseline characteristics are presented in Table 1.

Table 1 Baseline characteristics of the study population

Variable	Overall (N = 580)	No gingivitis (n = 261)	Gingivitis (n = 319)	P value
Age, Median (Q1, Q3)	13.00 (12.00, 14.00)	13.00 (12.00, 14.00)	13.00 (12.00, 15.00)	<0.001
Follow-up duration, months, Median (Q1, Q3)	16 (10, 22)	14 (8, 20)	17 (13, 25)	<0.001
MP–SN, Median (Q1, Q3)	34.8 (32.3, 37.6)	33.4 (30.3, 35.7)	36.2 (34.0, 39.1)	<0.001
FMA, Median (Q1, Q3)	26.4 (24.2, 28.9)	25.2 (22.1, 27.1)	27.4 (25.5, 30.2)	<0.001
ANB, Median (Q1, Q3)	5.20 (3.90, 6.30)	4.90 (3.80, 6.00)	5.40 (4.10, 6.50)	0.002
SNA, Median (Q1, Q3)	83.20 (81.20, 84.50)	83.30 (81.60, 84.80)	83.10 (81.00, 84.30)	0.146
SNB, Median (Q1, Q3)	78.0 (76.1, 80.0)	78.2 (76.3, 80.7)	77.8 (76.1, 79.4)	0.010
Facial angle, Median (Q1, Q3)	62.20 (60.85, 63.50)	61.60 (59.90, 62.90)	62.60 (61.50, 63.90)	<0.001
Sex, n (%)				0.013
Male	246 (42.4%)	96 (36.8%)	150 (47.0%)	
Female	334 (57.6%)	165 (63.2%)	169 (53.0%)	
Daily brushing ≥2 times/day, n (%)	425 (73.3%)	256 (98.1%)	169 (53.0%)	<0.001
Dental floss/interdental brush use, yes, n (%)	311 (53.6%)	155 (59.4%)	156 (48.9%)	0.012
Mouthwash use, yes, n (%)	211 (36.4%)	112 (42.9%)	99 (31.0%)	0.003
Toothbrush type, n (%)				0.977
Electric toothbrush	52 (9.0%)	22 (8.4%)	30 (9.4%)	
Orthodontic toothbrush	201 (34.7%)	91 (34.9%)	110 (34.5%)	
Soft-bristled toothbrush	295 (50.9%)	133 (51.0%)	162 (50.8%)	
Hard-bristled toothbrush	32 (5.5%)	15 (5.7%)	17 (5.3%)	
Orthodontic attachments, yes, n (%)	267 (46.0%)	96 (36.8%)	171 (53.6%)	<0.001
Orthodontic auxiliaries, yes, n (%)	151 (26.0%)	81 (31.0%)	70 (21.9%)	0.013
Orthodontic appliance type, n (%)				<0.001
Fixed appliances	544 (93.8%)	227 (87.0%)	317 (99.4%)	
Clear aligners	36 (6.2%)	34 (13.0%)	2 (0.6%)	
Secondhand-smoke exposure, yes, n (%)	97 (16.7%)	36 (13.8%)	61 (19.1%)	0.087

Variable	Overall (N = 580)	No gingivitis (n = 261)	Gingivitis (n = 319)	P value
Anxiety positive, n (%)	77 (13.3%)	6 (2.3%)	71 (22.3%)	<0.001
Depression positive, n (%)	75 (12.9%)	10 (3.8%)	65 (20.4%)	<0.001
Overbite, n (%)				0.928
Normal overbite	128 (22.1%)	57 (21.8%)	71 (22.3%)	
Grade I	115 (19.8%)	48 (18.4%)	67 (21.0%)	
Grade II	134 (23.1%)	63 (24.1%)	71 (22.3%)	
Grade III	157 (27.1%)	71 (27.2%)	86 (27.0%)	
Open bite	46 (7.9%)	22 (8.4%)	24 (7.5%)	
Overjet, n (%)				<0.001
Normal overjet	96 (16.6%)	72 (27.6%)	24 (7.5%)	
Grade I	100 (17.2%)	72 (27.6%)	28 (8.8%)	
Grade II	71 (12.2%)	40 (15.3%)	31 (9.7%)	
Grade III	206 (35.5%)	77 (29.5%)	129 (40.4%)	
Reverse overjet	107 (18.4%)	0 (0.0%)	107 (33.5%)	
Dental crowding, n (%)				0.035
Grade 0	102 (17.6%)	37 (14.2%)	65 (20.4%)	
Grade I	154 (26.6%)	83 (31.8%)	71 (22.3%)	
Grade II	94 (16.2%)	43 (16.5%)	51 (16.0%)	
Grade III	230 (39.7%)	98 (37.5%)	132 (41.4%)	
Angle classification, n (%)				0.115
Class I	209 (36.0%)	91 (34.9%)	118 (37.0%)	
Class II	320 (55.2%)	140 (53.6%)	180 (56.4%)	
Class III	51 (8.8%)	30 (11.5%)	21 (6.6%)	

Data are presented as median (Q1, Q3) or n (%). Continuous variables were compared using the Wilcoxon rank-sum test and categorical variables using Pearson's chi-squared test. Abbreviations: IQR, interquartile range; MP-SN, mandibular plane–sella–nasion angle; FMA, Frankfort–mandibular plane angle; ANB, A point–nasion–B point angle; SNA, sella–nasion–A point angle; SNB, sella–nasion–B point angle.

3.2 Cox regression analyses of factors associated with gingivitis onset

The univariable and multivariable Cox regression results are presented in Table 2. Orthodontic auxiliary use (adjusted HR, 1.56; 95% CI, 1.18–2.06), a positive anxiety screen (adjusted HR, 1.43; 95% CI, 1.09–1.89), and grade III increased overjet (adjusted HR, 1.65; 95% CI, 1.05–2.60) were associated with a higher hazard of gingivitis. Each 1° increase in MP–SN and FMA was associated with an approximately 3% (adjusted HR, 1.03; 95% CI, 1.00–1.06) and 4% (adjusted HR, 1.04; 95% CI, 1.00–1.08) higher hazard of gingivitis, respectively.

Brushing at least twice daily (adjusted HR, 0.78; 95% CI, 0.62–1.00) and treatment with clear aligners (adjusted HR, 0.24; 95% CI, 0.06–0.96) were associated with a lower hazard of gingivitis. However, only two events occurred in the clear aligner group, limiting the precision of the estimate. Grade III deep overbite was also associated with a lower hazard than normal overbite (adjusted HR, 0.68; 95% CI, 0.48–0.96). Age showed only a borderline association, and facial angle was not statistically significant after adjustment for other factors. Complete results are presented in Table 2.

Table 2 Univariable and multivariable Cox proportional hazards analyses

Variable	Univariable HR	95% CI	P value	Adjusted HR	95% CI	P value
Sex						
Male	Ref.	—				
Female	0.85	0.69–1.07	0.162			
Age	0.93	0.86–1.00	0.041	0.93	0.87–1.00	0.050
Daily brushing frequency						
≤1 time/day	Ref.	—		Ref.	—	
≥2 times/day	0.61	0.48–0.76	<0.001	0.78	0.62–1.00	0.048
Use of dental floss/interdental brush						
No	Ref.	—				
Yes	0.92	0.74–1.15	0.476			
Mouthwash use						
No	Ref.	—				
Yes	0.87	0.69–1.10	0.252			
Toothbrush type						
Electric toothbrush	Ref.	—				
Orthodontic toothbrush	1.13	0.75–1.69	0.559			
Soft-bristled toothbrush	0.84	0.56–1.24	0.368			
Hard-bristled toothbrush	0.75	0.41–1.35	0.333			
Orthodontic attachments						
No	Ref.	—				
Yes	0.89	0.72–1.12	0.328			
Use of orthodontic auxiliaries						
No	Ref.	—		Ref.	—	
Yes	1.47	1.12–1.93	0.005	1.56	1.18–2.06	0.002

Variable	Univariable HR	95% CI	P value	Adjusted HR	95% CI	P value
Orthodontic appliance type						
Fixed appliances	Ref.	—		Ref.	—	
Clear aligners	0.16	0.04–0.66	0.011	0.24	0.06–0.96	0.044
Secondhand-smoke exposure						
No	Ref.	—				
Yes	1.23	0.93–1.63	0.142			
Anxiety						
No	Ref.	—		Ref.	—	
Yes	1.62	1.24–2.10	<0.001	1.43	1.09–1.89	0.011
Depression						
No	Ref.	—				
Yes	1.26	0.96–1.65	0.102			
MP–SN	1.07	1.05–1.10	<0.001	1.03	1.00–1.06	0.044
FMA	1.09	1.06–1.12	<0.001	1.04	1.00–1.08	0.047
ANB	1.01	0.97–1.05	0.638			
SNA	0.97	0.93–1.01	0.161			
SNB	1.00	1.00–1.00	0.838			
Facial angle	1.12	1.07–1.18	<0.001	1.02	0.97–1.09	0.411
Overbite						
Normal overbite	Ref.	—		Ref.	—	
Grade I	0.91	0.66–1.26	0.583	0.89	0.64–1.24	0.482
Grade II	0.87	0.63–1.21	0.412	0.97	0.70–1.36	0.879
Grade III	0.62	0.44–0.87	0.005	0.68	0.48–0.96	0.029
Open bite	0.97	0.61–1.54	0.889	0.84	0.52–1.37	0.493
Overjet						
Normal overjet	Ref.	—		Ref.	—	
Grade I	1.55	0.90–2.67	0.118	1.43	0.82–2.49	0.202
Grade II	1.65	0.97–2.82	0.065	1.30	0.75–2.25	0.352
Grade III	2.27	1.47–3.51	<0.001	1.65	1.05–2.60	0.029
Reverse overjet	2.45	1.56–3.84	<0.001	1.58	0.98–2.55	0.060
Dental crowding						
Grade 0	Ref.	—				
Grade I	0.98	0.70–1.37	0.891			

Variable	Univariable HR	95% CI	P value	Adjusted HR	95% CI	P value
Grade II	1.36	0.94–1.96	0.106			
Grade III	0.91	0.67–1.22	0.518			
Angle classification						
Class I	Ref.	—				
Class II	0.86	0.68–1.09	0.215			
Class III	0.74	0.47–1.18	0.206			

HR, hazard ratio; CI, confidence interval; Ref., reference category. Blank adjusted cells indicate variables not retained in the multivariable model.

3.3 Feature selection and cumulative hazard curves

The Boruta analysis confirmed seven important features: daily toothbrushing frequency, MP–SN, FMA, anxiety, depression, overjet, and sGn–FH (Fig. 1). Five predictors were identified by both Boruta and multivariable Cox regression: daily toothbrushing frequency, MP–SN, FMA, anxiety, and overjet (Online Resource 1, Fig. S1). These five variables were included in the final Cox prediction model.

The stratified cumulative hazard curves showed separation across overjet categories (Fig. S2A in Online Resource 1). Cumulative hazard was higher among patients with a positive anxiety screen than among those with a negative screen (log-rank $P < 0.001$; Fig. S2B). Patients treated with fixed appliances had higher cumulative hazard than those treated with clear aligners (log-rank $P < 0.001$; Fig. S2C). Cumulative hazard was also higher among patients who used orthodontic auxiliaries than among those who did not (log-rank $P < 0.001$; Fig. S2D).

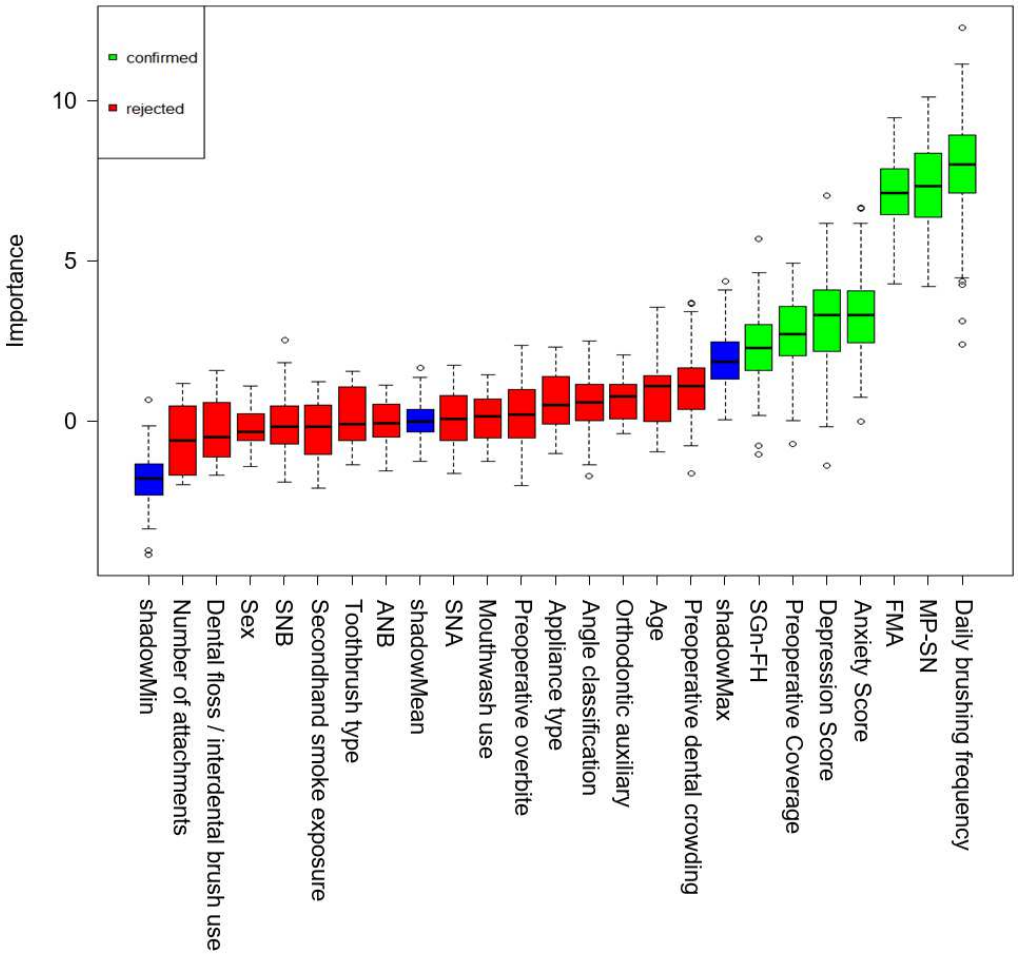

Fig. 1 Feature importance identified using the Boruta algorithm. Green boxes denote confirmed important variables, red boxes denote rejected variables, and blue boxes represent shadow features used as references

3.4 Discrimination, calibration, and clinical utility of the prediction model

The Cox prediction model comprising the five predictors identified by both methods had an apparent C-index of 0.677. The time-dependent AUCs at 12, 24, and 36 months were 0.723 (95% CI, 0.636–0.811), 0.716 (95% CI, 0.610–0.822), and 0.857 (95% CI, 0.681–1.033), respectively, indicating moderate apparent discrimination (Fig. 2).

The Brier scores at 12, 24, and 36 months were 0.032 (95% CI, 0.021–0.042), 0.048 (95% CI, 0.037–0.060), and 0.063 (95% CI, 0.049–0.077), respectively. Predicted and observed risks were generally close across the range of predicted probabilities shown in the calibration plots (Fig. 3). Apparent decision-curve analysis indicated that the model yielded greater net benefit than the treat-all and treat-none strategies over some low-to-moderate threshold probability ranges (Fig. 4A–C).

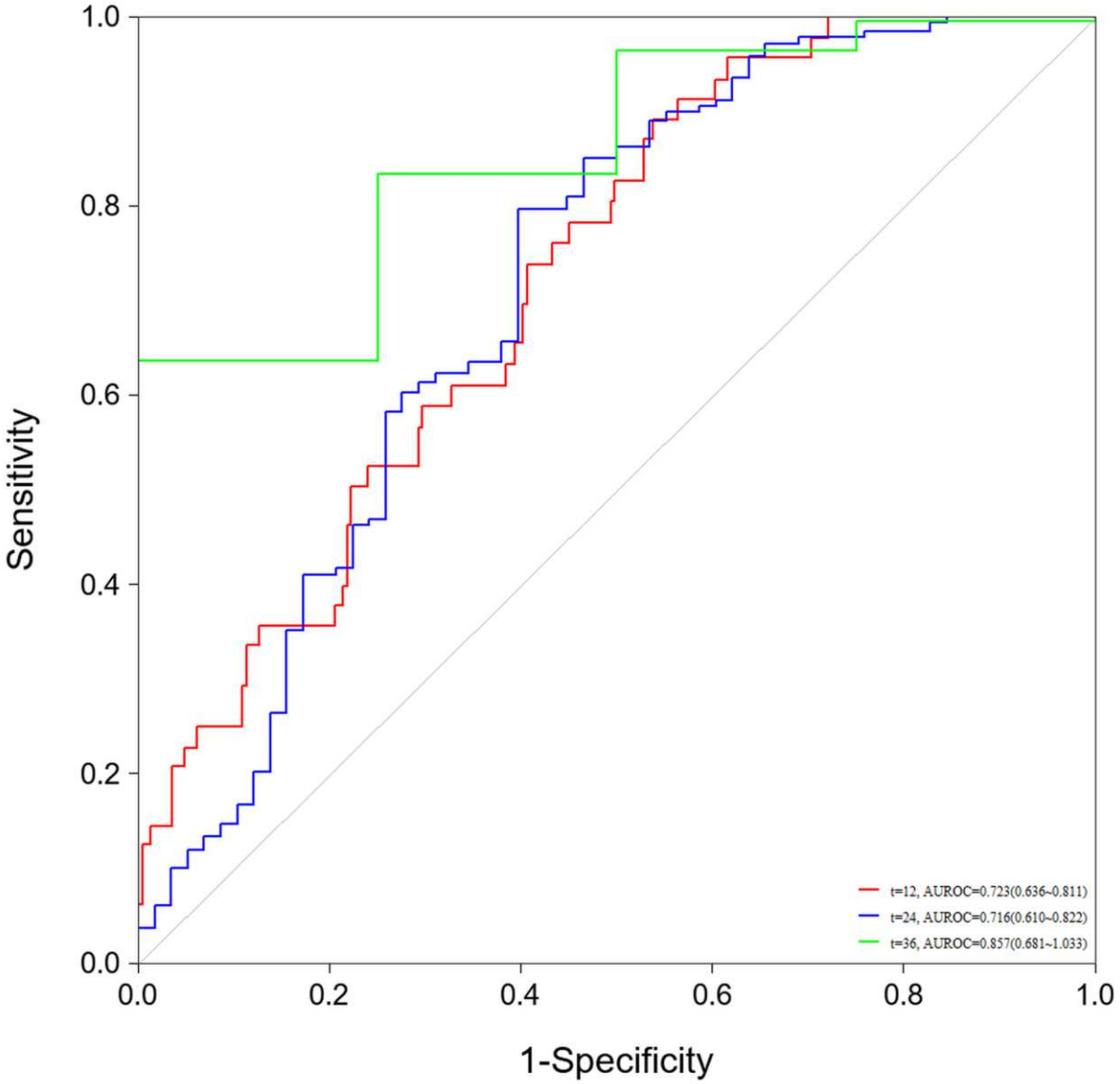

Fig. 2 Apparent time-dependent receiver operating characteristic curves of the Cox prediction model at 12, 24, and 36 months. The corresponding AUC point estimates were 0.723, 0.716, and 0.857, respectively

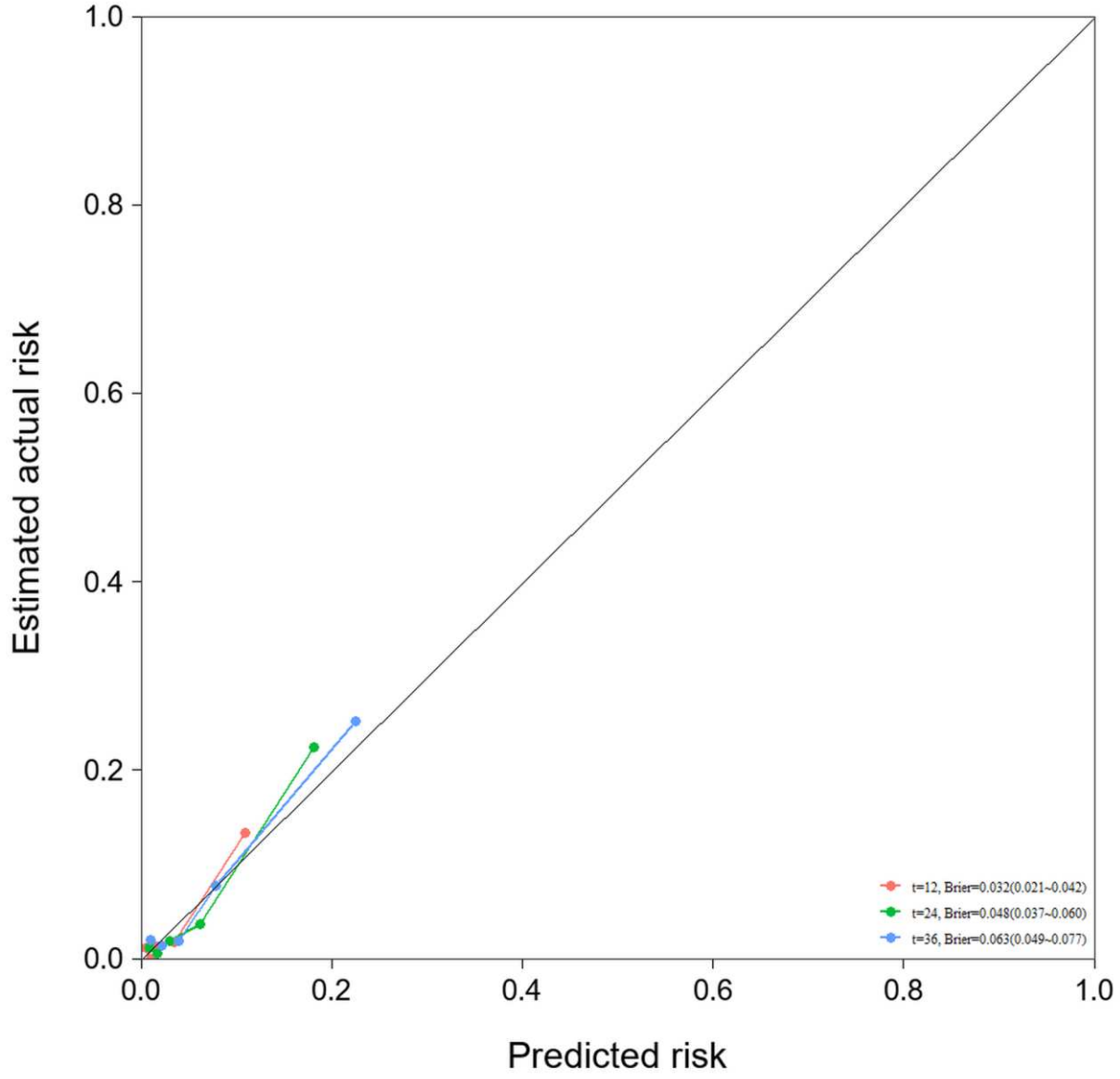

Fig. 3 Apparent calibration curves of predicted versus observed gingivitis risk at 12, 24, and 36 months. The corresponding Brier scores were 0.032, 0.048, and 0.063, respectively. The diagonal line indicates perfect calibration

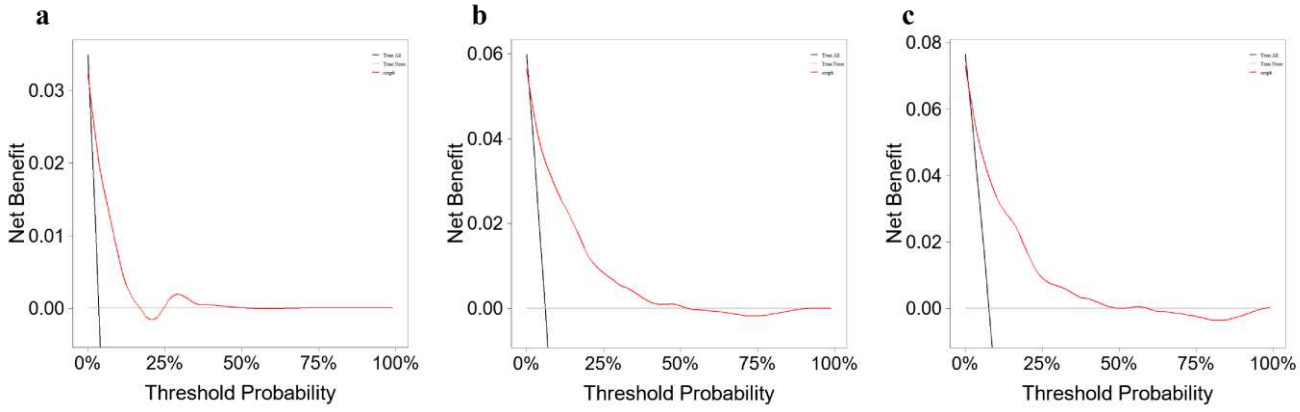

Fig. 4 Apparent decision-curve analysis at (A) 12, (B) 24, and (C) 36 months. Red: model; black: treat all; gray: treat none

4 Discussion

4.1 Main findings and comparison with previous studies

Among the 580 adolescent orthodontic patients with follow-up data, 319 (55.0%) developed gingivitis during follow-up. Multivariable Cox analysis showed that daily toothbrushing frequency, use of orthodontic auxiliaries, appliance type, a positive anxiety screen, MP–SN, FMA, overbite, and overjet were independently associated with time to gingivitis onset. Boruta and multivariable Cox regression jointly identified five predictors: daily toothbrushing frequency, MP–SN, FMA, a positive anxiety screen, and overjet. These findings suggest that oral hygiene behavior, psychological status, and craniofacial morphology may provide complementary information for risk stratification during orthodontic treatment in adolescents.

The proportion of patients who developed gingivitis during follow-up was 55.0%, higher than the prevalence reported in some cross-sectional surveys of the general adolescent population in China. This difference may reflect variation in study populations, diagnostic criteria, and observation methods. Orthodontic brackets, archwires, and other components increase plaque retention and make cleaning more difficult. Previous research has reported greater plaque retention and gingival inflammation in patients with fixed appliances than in individuals who had not undergone orthodontic treatment [14]. Gingival index scores and levels of periodontal-associated microorganisms may increase early after fixed appliance placement and partially decrease as oral hygiene improves [15]. These observations suggest that gingivitis risk varies over time and may be amenable to intervention.

4.2 Oral hygiene behavior and orthodontic treatment-related factors

Oral hygiene behavior is a major factor associated with gingivitis risk. Brushing at least twice daily was associated with a significantly lower risk of gingivitis, consistent with a national adolescent survey showing progressively higher risks of localized and generalized gingivitis as toothbrushing frequency decreased. In patients with fixed appliances, plaque accumulates predominantly gingival to the brackets, on proximal surfaces, and behind archwires, whereas more frequent toothbrushing is associated with less biofilm accumulation [16]. Toothbrushing frequency may therefore reflect both mechanical plaque control and patients' treatment adherence and motivation to maintain their oral health. However, the adjusted effect reported in the combined regression table was modest, and the upper confidence limit was close to 1.00. Although statistically significant, this finding requires further validation incorporating brushing technique and duration, fluoride toothpaste use, and objective plaque measures.

Use of orthodontic auxiliaries was associated with a higher risk of gingivitis, possibly because additional bands, connectors, or palatal components create plaque-retentive sites and restrict access for toothbrushes and interdental cleaning aids. Clear aligners were associated with a lower risk than fixed appliances. This direction of association is consistent with reviews reporting slightly better short- to medium-term plaque and gingival inflammation outcomes with clear aligners, potentially because they can be removed for eating and cleaning. However, these reviews also note that some differences are small in clinical magnitude [17]. In the present study, only 36 patients received clear aligners, and only two events occurred in this group, resulting in a wide

confidence interval for the HR. The association may therefore be confounded by treatment indication, case complexity, patient motivation, and adherence, and should not be used alone to determine appliance selection.

4.3 Anxiety and gingivitis risk

A positive anxiety screen was independently associated with a higher risk of gingivitis, representing one of the more clinically relevant findings of this study. Two interacting pathways may be involved. First, anxiety may impair adherence to regular oral hygiene and follow-up visits and reduce proactive oral healthcare seeking. Second, sustained psychological stress may influence periodontal tissue responses through the hypothalamic–pituitary–adrenal axis, autonomic activity, and immune and inflammatory regulation. Systematic reviews of adult studies suggest an association of psychological stress and anxiety with periodontal disease [18, 19]. However, evidence in adolescents remains inconsistent. After adjustment for oral hygiene, orthodontic appliances, and other factors, the LIFE Child study found no consistent associations of cortisol or dehydroepiandrosterone sulfate (DHEA-S) with early periodontal probing abnormalities [20]. The present finding should therefore be interpreted as a risk marker rather than a causal effect. Future studies should jointly assess changes in anxiety over time, adherence to toothbrushing, sleep, salivary flow rate, and inflammatory biomarkers to distinguish behavioral from biological pathways.

4.4 Craniofacial morphology and overjet

Larger MP–SN and FMA angles and grade III increased overjet were associated with a higher risk of gingivitis, suggesting that vertical skeletal pattern and anterior tooth relationships may provide risk information beyond conventional oral hygiene measures. Previous pediatric research has also reported an association between increased overjet and gingivitis, while another study linked increased overjet and anterior open bite to moderate-to-severe gingivitis [21].

One possible explanation is that patients with a high-angle skeletal pattern are more likely to have lip incompetence or mouth breathing. These conditions may dry the gingival surface in the anterior region, hinder plaque removal, and increase susceptibility to local inflammation [22, 23]. A systematic review found that children and adolescents who breathe through the mouth more frequently exhibit larger mandibular plane angles and a vertical growth pattern [24]. This provides indirect support for the mechanistic hypothesis.

Breathing mode, lip competence, and the sites of inflammation were not assessed in this study. Consequently, these findings cannot directly establish that MP–SN or FMA contributes to gingivitis through mouth breathing. The estimated effects per unit increase in both angles were also small; clinical interpretation should therefore consider risk along a continuum rather than rely on simple cutoffs.

Grade III deep overbite was associated with a lower risk of gingivitis in this study. This finding differs from reports in some previous studies linking deep overbite to gingival bleeding, increased probing depth, and periodontal tissue damage. Gingivitis is primarily caused by sustained accumulation of dental plaque biofilm, whereas abnormal occlusal forces associated with deep overbite mainly affect the periodontal supporting tissues and may not directly induce gingivitis [25, 26].

Furthermore, patients with severe deep overbite typically have a characteristic vertical craniofacial morphology and may receive targeted interventions, such as bite opening, during treatment [27]. When MP–SN, FMA, and other treatment-related factors are included in the same model, collinearity, treatment effects, or residual confounding may influence the estimated association between deep overbite and gingivitis risk [28]. The present findings are therefore insufficient to establish an independent biological protective effect of grade III deep overbite. Its clinical relevance requires further validation with adjustment for baseline plaque levels, gingival status, treatment stage, and adherence to oral hygiene.

4.5 Candidate predictors and model performance

Cox regression and Boruta jointly selected five variables spanning behavioral, psychological, and craniofacial morphological domains. The partial agreement between these methods suggests that these variables may be candidate predictors of gingivitis onset. Depression scores and sGn–FH were selected only by Boruta, possibly because of nonlinear relationships, interactions between variables, or random variation. In contrast, use of orthodontic auxiliaries and appliance type were retained only in the Cox model, indicating that variable selection may be influenced by model assumptions and correlations among variables. Variable importance should therefore not be equated with an independent association or a causal effect, and taking the intersection of variables selected by the two methods does not replace model validation.

The final Cox model had an apparent C-index of 0.677, indicating moderate discrimination. Although it could distinguish to some extent between orthodontic patients at different risks of gingivitis, its predictive performance does not yet support direct clinical use. Its potential value lies in helping identify high-risk patients who may require enhanced oral hygiene instruction and periodontal monitoring, rather than serving as a stand-alone clinical decision tool. Because performance was assessed using the model development data, the estimates may be optimistic. Future studies should undertake internal validation using bootstrapping or repeated cross-validation and report the optimism-corrected C-index, calibration intercept, calibration slope, Brier score, and time-dependent AUC. External validation across healthcare institutions and populations using different appliance types is then needed to assess generalizability and clinical net benefit. Model development and reporting may follow the TRIPOD+AI guidance to improve transparency in feature selection, performance assessment, and validation [29].

4.6 Clinical implications

These findings support risk-stratified prevention before and during orthodontic treatment. Potentially higher-risk patients include those who brush fewer than twice daily, require complex orthodontic auxiliaries, or screen positive for anxiety. Larger MP–SN or FMA angles and increased anterior overjet may also indicate higher risk. For these patients, more intensive individualized toothbrushing and interdental cleaning instruction and shorter intervals between periodontal assessments could be considered. Plaque and gingival bleeding could also be reassessed at each orthodontic visit. Clear communication, predictable treatment procedures, and psychological support when needed may help improve adherence in patients with anxiety symptoms. Selection of appliances and orthodontic auxiliaries should continue to prioritize biomechanical requirements and

correction of malocclusion. Periodontal risk should provide supplementary information for shared decision-making and the intensity of follow-up, rather than serve as the sole determinant.

5 Conclusions

Adolescent orthodontic patients experienced a substantial burden of gingivitis during follow-up. Less frequent daily toothbrushing, use of orthodontic auxiliaries, a positive anxiety screen, larger MP–SN and FMA angles, and increased overjet were associated with higher risk, while risk may differ between appliance types. The agreement between Cox regression and Boruta supports incorporating oral hygiene behavior, psychological status, and craniofacial morphology into risk assessment. Multicenter prospective studies and rigorous model validation are needed to confirm these findings and determine whether intensified prevention based on risk stratification can reduce the occurrence of gingivitis.

Declarations

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Competing interests The authors declare no competing interests.

Ethics approval This study was approved by the Ethics Committee of Union Hospital, Tongji Medical College, Huazhong University of Science and Technology (approval No. KQHL20260704) and was conducted in accordance with the Declaration of Helsinki.

Consent to participate Written informed consent for the anonymous use of medical records was obtained from the participants or their guardians.

Consent to publish Not applicable.

Data availability The de-identified data supporting the findings of this study are available from the corresponding author upon reasonable request, subject to applicable ethics approval and privacy requirements.

Author contributions Li Hu, Jinyu Wang contributed to the study design. Xianzhe He, Yulu Yan, Hanni Fu, Haiqing Huang, Yifei Huo, Yi Zhou, and Youtao Liu contributed to data collection and processing.

Supplementary information

Online Resource 1 Supplementary figures showing the overlap of variables selected by Cox regression and Boruta and stratified cumulative hazard curves

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