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Evaluation of palatal mucosal thickness in maxillary posterior teeth using cone-beam computed tomography combined with intraoral scanning: a cross-sectional study on correlating factors

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Abstract

Objectives Cone-beam computed tomography (CBCT) combined with intraoral scanning (IOS) technology was used to measure and analyze the variation patterns of the palatal masticatory mucosa (PMM) in the maxillary posterior region and its correlation with gender, gingival biotype (GB), and the palatal bone thickness (PBT), thereby establishing a theoretical foundation for autogenous soft tissue augmentation procedures.

Materials and methods A total of 57 Han Chinese patients and 342 affected teeth were included in the study. CBCT and IOS data were obtained for all participants, and 3D models were constructed by segmenting CBCT images based on standardized parameters, followed by alignment with IOS data using reference points. Measurements were conducted at predetermined intervals to evaluate PMM, PBT, and GB. The variability of PMM from the first premolar to the first molar was analyzed bilaterally by gender, age, and GB using t-tests and Games-Howell post-hoc analysis. Pearson's correlation test examined the relationship between PMM and PBT, while linear regression models were utilized to evaluate associations between PMM and clinical factors such as gender, age, and PBT.

Results There was no statistically significant difference in PMM between the left and right sides of the maxilla ($P > 0.05$). Overall, PMM increased with greater distance from the gingival margin, and statistically significant differences were observed between specific measurement points at different tooth positions. The second premolar exhibited the greatest thickness at 6 mm, 8 mm, and 10 mm. Gender had a relatively minor impact on PMM. Significant differences in PMM were observed across age groups, with the middle-aged group showing greater PMM compared to the younger group ($P < 0.05$). At 2 mm from the first molar's gingival margin, significant PMM differences

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were identified between different GB ($P < 0.05$). The correlation between PBT and PMM was weak. Regression analysis revealed age as a primary determinant of PMM, with gender and PBT exerting site-specific effects.

Conclusions CBCT combined with IOS proved effective in measuring maxillary PMM. The maxillary posterior region exhibited a symmetrical distribution of PMM, with premolar areas identified as optimal for soft tissue graft harvesting. While no significant correlation was found with gender, GB, or PBT, the mucosa was notably thicker in middle-aged individuals.

Clinical relevance This study presents comprehensive data on PMM thickness across various tooth positions and distances from the gingival margin, facilitating the identification of optimal donor sites for autologous grafts. It highlights regional and ethnic variations in PMM thickness among Han Chinese patients and validates the combined use of CBCT and IOS for accurate, non-invasive measurements.

Keywords CBCT, IOS, Palatal mucosal thickness, Autologous grafts

Introduction

The success of dental implants is strongly linked to the health of the surrounding soft tissues. Implant success depends not only on the stability of osseointegration but also heavily on the condition of these tissues [1, 2]. With deeper insights into peri-implant soft tissue biology, growing evidence highlights the critical role of soft tissue management in achieving long-term functional and aesthetic outcomes [3]. Soft tissue enhancement techniques, particularly autologous grafts like free gingival grafts (FGGs) and connective tissue grafts (CTGs), are essential for maintaining peri-implant health and stability in the medium to long term [4]. These grafts are widely used in periodontal and peri-implant procedures to cover root surfaces, increase keratinized tissue width, and augment soft tissue volume around natural teeth and implants.

The hard palate and maxillary tuberosity serve as primary donor sites for autologous soft tissue grafts, with the hard palate favored for its collagen-rich lamina propria, ensuring structural integrity and optimal healing [5]. Research confirms that the hard palate's lamina propria and submucosa, abundant in type I collagen, are well-suited for graft integration and healing [6, 7]. Critical factors, including the thickness of the palatal mucosa and the positioning of the major palatal neurovascular bundle, dictate the size of autologous soft tissue grafts that can be safely harvested [8]. Due to the distinctive anatomy of the palate, meticulous attention is required during soft tissue grafting to avert any potentially serious complications [9]. Any injury to the neurovascular bundle in this region may result in adverse outcomes such as sensory disturbances or hemorrhage. Additionally, certain graft dimensions (width, thickness, and surface area) and the extent of intraoperative preparation are crucial determinants of surgical success [10, 11]. In particular, the excessive graft thickness may hinder vascular regeneration, delaying healing and causing necrosis at both the donor and recipient sites, as well as prolonging wound recovery and increasing patient discomfort [12, 13]. On the other hand, although preserving a residual palatal flap thickness of at least 1 mm can reduce patient discomfort and promote healing, a reduced graft thickness is associated with an increased risk of palatal flap dehiscence/necrosis during the healing period, thereby elevating morbidity rates [14, 15]. This heightened risk arises from their reduced capacity to withstand mechanical stress and maintain sufficient blood supply [16]. However, soft tissue donor sites differ among individuals, and even gingival thickness and histological composition can vary within the same patient [17–19]. It is worth noting that the variation in the palatal masticatory mucosa (PMM) with age is due to the excess deposition of adipose tissue, mucous glands, the high prevalence of exostoses, and gingival recession [8]. Differences in parameters such as the palatal bone thickness (PBT) and gingival biotype (GB) also influence graft selection and surgical planning [20]. These variables must be carefully considered during surgery, and it is highly recommended that PMM be evaluated beforehand [21].

Methods for measuring palatal soft tissue thickness are either invasive or non-invasive. Invasive techniques require local anesthesia, are traumatic, and poorly accepted by patients [22, 23]. Non-invasive imaging modalities, such as ultrasound, magnetic resonance imaging (MRI), and cone-beam computed tomography (CBCT), exhibit limitations when used independently [24–26]. In recent years, intraoral scanning (IOS) has become an increasingly vital tool for measuring soft tissues, offering precise digital reconstructions of teeth and soft tissues that can be seamlessly integrated with CBCT data [27]. Our prior research demonstrated that integrating CBCT with IOS significantly enhances the accuracy and efficiency of soft-tissue measurements, thereby providing invaluable insights for aesthetic restorations and implant procedures in dentistry [28].

To the best of our knowledge, non-invasive examinations using CBCT combined with IOS data have rarely focused on patients from the Han Chinese ethnic group. Our decision to conduct this study was motivated by the limited understanding of regional variations in PMM.

Therefore, this study aimed to analyze the thickness of the palatal mucosa in the maxillary posterior region of Han Chinese patients, in combination with CBCT and intraoral scans, and to correlate it with factors such as gender, GB, and PBT to identify the optimal graft donor area.

Materials and methods

Study design

A total of 57 patients, including both the bilateral maxillary first premolar to first molar PMM and the corresponding palatal bone tissue, were analyzed in this cross-sectional study. The cohort comprised 25 males and 32 females, with a mean age of 34.98 ± 13.67 (range: 18–70) years. To facilitate the comparison between age and PMM, adult patients included in the study who were 40 years old or younger were classified as the young group, while those older than 40 were classified as the middle-aged group. All participants were of Han Chinese ethnicity. The study was approved by the Ethics Committee of School and Hospital of Stomatology, Cheeloo College of Medicine, Shandong University (approval number: NO.20200502) and adhered to the principles of the 2013 revision of the 1975 Declaration of Helsinki. Written and verbal explanations were provided, and all participants gave informed consent in writing.

Sample collections

The sample size was determined using G*Power 3.1.9.7 software, with an effect size (f) of 0.637 based on previous study results [8]. An ANOVA was conducted with an alpha level of 0.05 and a beta of 0.1 (power = 90%), establishing a minimum requirement of 48 participants. Consequently, 57 participants and 342 teeth were included in the study.

We enrolled patients at the Department of Implantology, School of Stomatology, Shandong University, to undergo IOS between December 2020 and March 2022. CBCT and IOS data were obtained from all participants.

The inclusion criteria were: (1) age between 18 and 70 years; (2) nonsmoker; (3) complete dentition in the maxillary posterior region (with or without third molar), healthy periodontal tissues, probing depth ≤ 3 mm, and bleeding index ≤ 2; and (4) no crossbite in the anterior teeth or known oral parafunction.

Exclusion criteria were: (1) the presence of any syndrome or systemic disease affecting bone and soft tissue health; (2) a history of maxillary palatal disease or surgery; (3) past or current use of medications associated with gingival enlargement; (4) pregnancy or lactation; (5) a history of orthodontic treatment; (6) missing, ectopic, or spaced maxillary teeth; and (7) CBCT scans revealed pathological conditions along with motion artifacts or other significant distortions.

The demographic data of all patients were retrieved from their medical records, and all participants received oral hygiene instructions and motivation.

Data Preparation

Imaging data were obtained using a CBCT device (New Tom 5G, Italy) under standardized conditions and saved as.dcm files. All scans were performed at 110 kV and 10 mA for 18 s (voxel size: 0.3 mm; grayscale: 16 bits; focal spot: 0.3 mm; and field of view: 18 × 16 cm). IOS was performed by experienced technicians using an intraoral scanner (TRIOS, 3Shape, Copenhagen K, Denmark). The chair position for the oral scanning procedure was selected to maximize both patient comfort and clinician efficiency. Preparations ensured a clear view, free from saliva, food debris, or blood contamination. Tooth surfaces were thoroughly dried, and a saliva suction device was employed. An optical impression of the subject's maxillary dentition was then taken, following the same scanning sequence (occlusal-palatal-labial) under natural lighting. The buccal side was scanned up to the vestibular groove, and the palatal side included the entire palate.

The registration of CBCT and IOS was performed using a surface-based approach. IOS data were saved and exported in ".stl" format. The subject's CBCT data, in ".dcm" format, were imported into the implant guide software (Simplant Pro 17; Dentsply Sirona, York, PA, USA). A threshold range of [600, 3071] was selected during the segmentation of the CBCT dataset to create a mask. The mask preserved the maxilla and teeth by connecting the regions above the bilateral infra zygomatic crest. Each slice was thoroughly checked manually, with the process involving the delineation of orthogonal CBCT planes. Any incorrectly segmented voxels in the final mask were adjusted using manual editing tools. The mask was then converted into a 3D object. Subsequently, the maxillary IOS data were imported and aligned with the CBCT data using corresponding marked points on the teeth. As in our previous methods, a preliminary rough alignment was achieved by manually selecting six reference points: the mesial buccal tips of the bilateral first molars, the buccal tips of the first premolars, and the incisal edges of the central incisors [28]. After performing translational and rotational adjustments based on these reference points, the registration results were validated by inspecting the alignment contours of the data (Fig. 1).

Measurements on CBCT + IOS images

The images were standardized before measurement. In the transverse plane, the measurement plane was aligned with the buccal and lingual cusps of the first and second premolars, as well as the buccal groove and mesial cusp of the first molar. In the bucco-lingual plane, it was

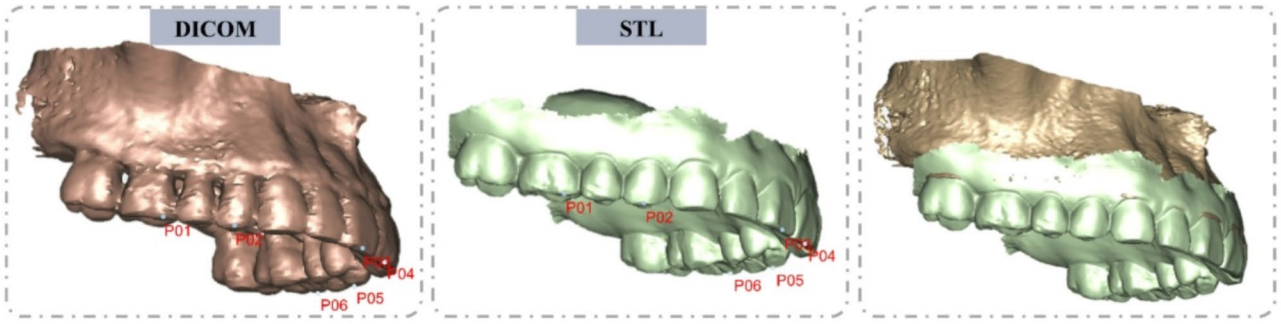

Fig. 1 Composite illustrating the registration process of DICOM and STL files using six reference points (P01, P06: the mesial buccal tips of the first molars; P02, P05: the buccal tips of the first premolars; P03, P04: the incisal edges of the central incisors)

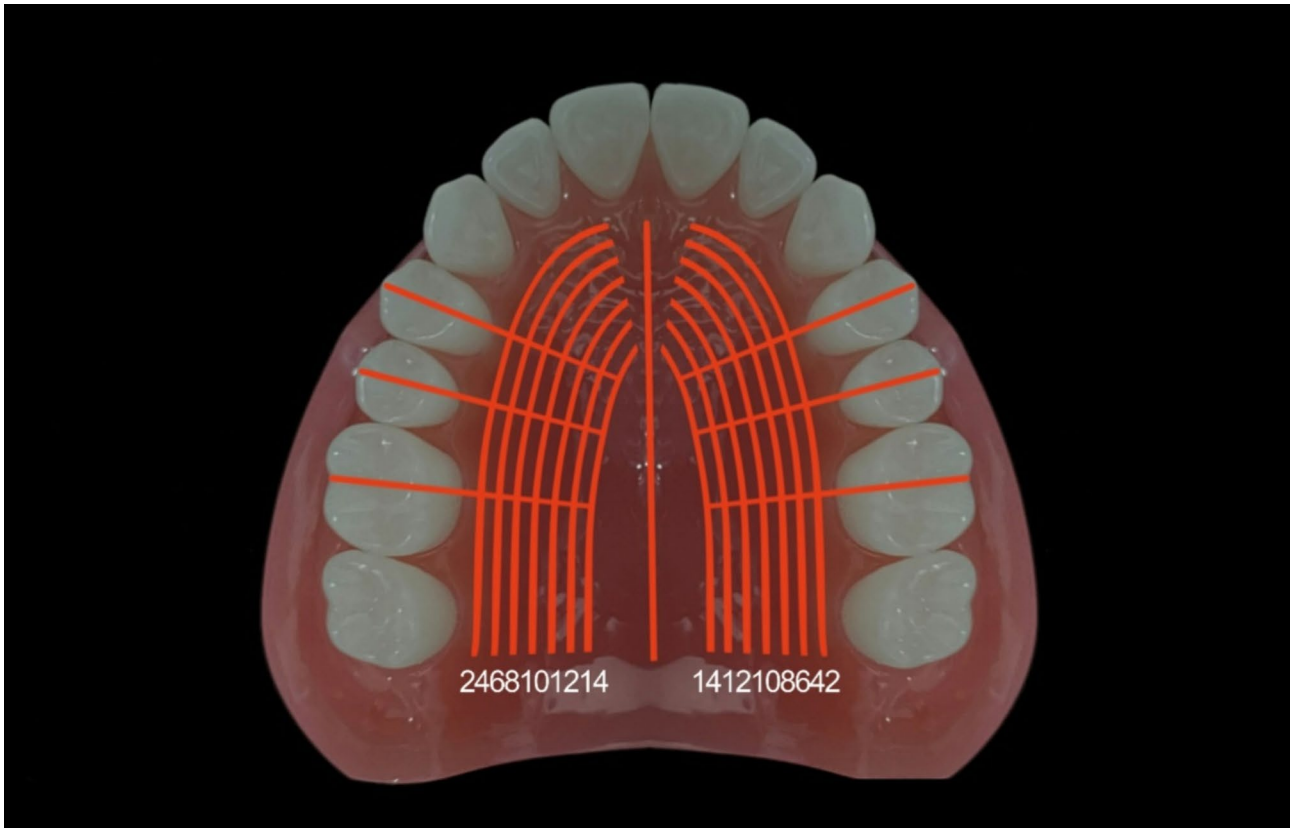

Fig. 2 Measurement model of PMM from the first premolar to the first molar bilaterally in the maxilla, at 2 mm to 14 mm from the gingival margin

parallel to the long axis of the teeth (with molars parallel to the palatal root), ensuring correct axial alignment for each tooth position (Figs. 2 and 3). The measurement methods were based on studies by Couso-Queiruga et al. [29], Song et al. [30], and Chow et al. [31].

1. PMM is measured in the bucco-lingual plane, using the vertical distance from the STL data contour to the bone surface. Measurement points are taken at 2 mm, 4 mm, 6 mm, 8 mm, 10 mm, 12 mm, and 14 mm from the palatal gingival margin (Fig. 4A).
2. PBT was measured using the alveolar crest of the maxillary posterior teeth as the reference point. Vertical lines were drawn perpendicular to the tooth's long axis at intervals of 2 mm, 4 mm, 6 mm, 8 mm, and 10 mm, and the intersections of these lines with the bone plate were recorded (Fig. 4B).
3. The labial masticatory mucosa (LMM) is measured in the bucco-lingual plane by drawing a vertical line perpendicular to the long axis of the tooth, positioned 1 mm below the labial gingival margin of tooth 11. The distance between the STL data contour and the tooth surface is recorded to classify the GB

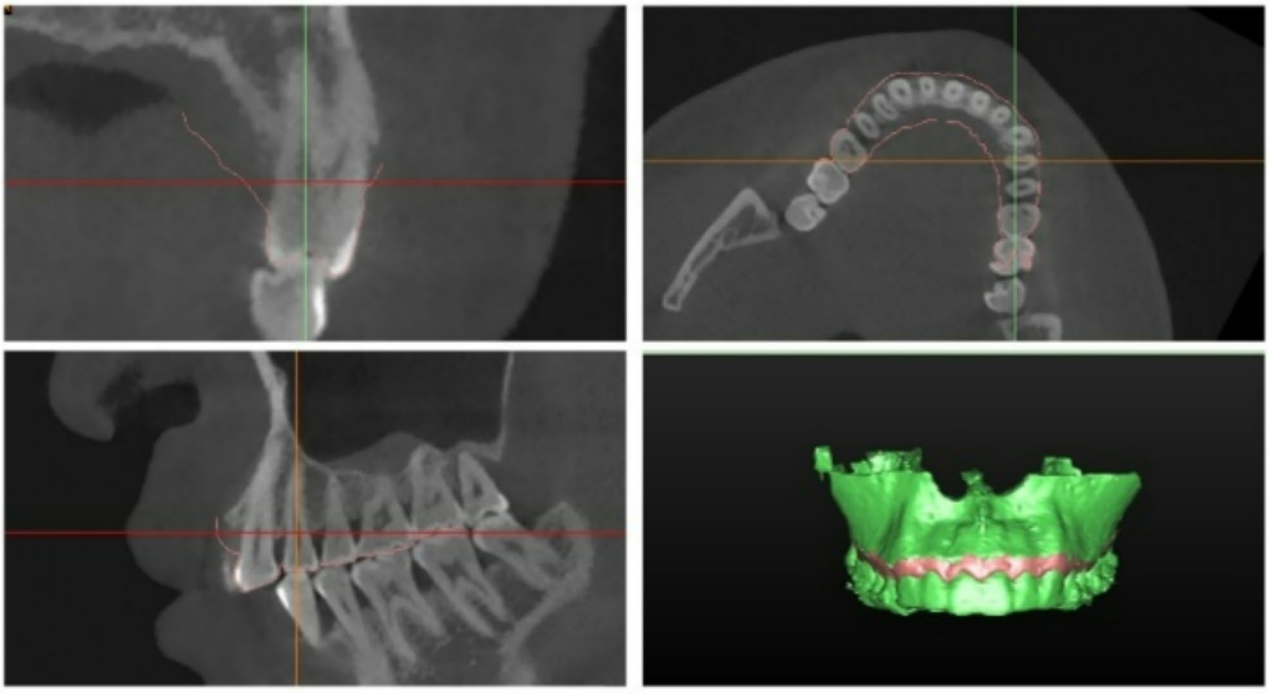

Fig. 3 Localization model of PMM for a single tooth

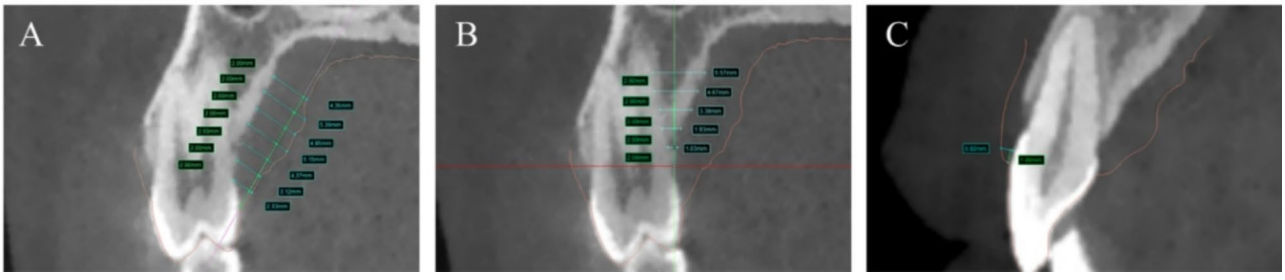

Fig. 4 Measurement model for a single tooth: (**A**) The palatal masticatory mucosa. (**B**) The palatal bone thickness. (C) The labial masticatory mucosa

(Fig. 4C). LMM ≥ 1 mm is defined as a thick biotype, while thickness < 1 mm is classified as a thin biotype, and these measurements are used for further analysis [32].

All data measurements were conducted by a single examiner (S.S.), proficient in dental imaging software applications, following a standardized protocol. To ensure objectivity, the blinded assessor (unaware of clinical parameters) performed all evaluations using identical equipment throughout the study. Measurements were taken at one-week intervals, with three independent sessions completed, after which the average value was calculated. The data comprised the three aforementioned measurements from the maxillary first premolar to the first molar on both sides for each patient, amounting to 2,394 PMM points, 1,710 PBT points, and 57 LMM points.

Statistical analysis

Statistical analyses were conducted using IBM SPSS Statistics 26.0. The coefficient of variation (CV), a percentage ratio of standard deviation to mean, was computed for each point to evaluate the consistency and relative variability of repeated measurements. T-tests were employed for normally distributed data, while non-parametric tests were used for non-normally distributed data. Independent t-tests were used to compare differences in PMM between the left and right sides of the maxilla, between genders, and between GB. ANOVA was applied to assess differences in PMM across various tooth positions and measurement points. If significant differences were found, Games-Howell post-hoc tests were performed for pairwise comparisons. Pearson correlation analysis evaluated the relationship between PMM and the corresponding PBT in the maxillary posterior region. To evaluate the association between PMM and clinical factors (gender, age, and PBT), linear regression

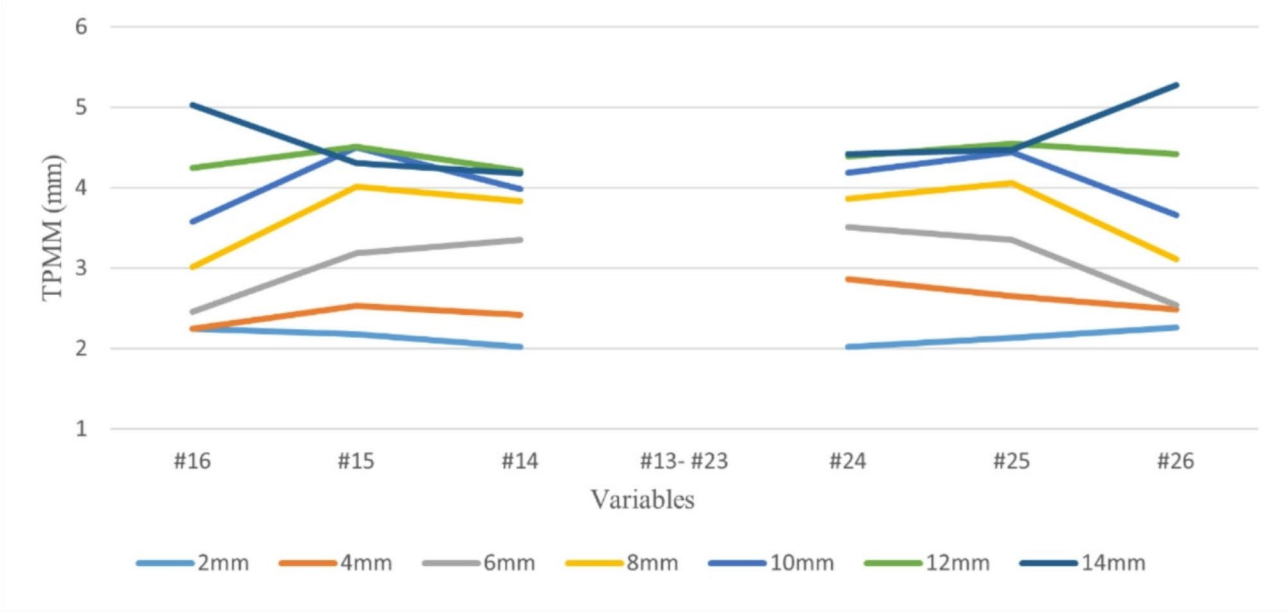

Fig. 5 Distribution of palatal mucosal thickness on both sides of the maxilla

Table 1 PMM (mm) at different levels of the same tooth position

Variables	2 mm	4 mm	6 mm	8 mm	10 mm	12 mm	14 mm	*F*
14	2.02 ± 0.64^{c}	2.42 ± 0.82^{c}	3.35 ± 0.64^{b}	3.83 ± 0.70^{a}	3.98 ± 0.75^{a}	4.21 ± 0.89^{a}	4.18 ± 0.93^{a}	73.526^{***}
15	2.18 ± 0.55^{f}	2.53 ± 0.63^{e}	3.19 ± 0.62^{d}	4.01 ± 0.75^{ac}	4.50 ± 0.85^{ab}	4.51 ± 1.07^{a}	4.31 ± 0.97^{a}	84.362^{***}
16	2.25 ± 0.60^{e}	2.25 ± 0.60^{e}	2.46 ± 0.65^{e}	3.01 ± 0.84^{d}	3.58 ± 1.07^{c}	4.25 ± 1.26^{b}	5.03 ± 1.35^{a}	69.426^{***}
24	2.02 ± 0.50^{e}	2.86 ± 0.78^{d}	3.51 ± 0.83^{c}	3.86 ± 0.85^{ac}	4.19 ± 0.90^{a}	4.39 ± 0.95^{ab}	4.42 ± 1.22^{a}	58.031^{***}
25	2.13 ± 0.46^{d}	2.65 ± 0.08^{c}	3.35 ± 0.76^{b}	4.06 ± 0.87^{a}	4.44 ± 0.81^{a}	4.55 ± 1.00^{a}	4.47 ± 0.97^{a}	82.919^{***}
26	2.26 ± 0.57^{e}	2.49 ± 0.84^{e}	2.54 ± 0.86^{e}	3.11 ± 0.85^{d}	3.66 ± 0.91^{c}	4.42 ± 1.08^{b}	5.28 ± 1.39^{a}	78.663^{***}

The same letters in the same line indicate no significant difference ($P>0.05$), the different letters in the same line indicate the significant difference ($P<0.05$). Significant differences in PMM at different measurement points of the same tooth position (: $p<0.05$, **: $p<0.01$, ***: $p<0.001$)

models were applied at different measurement distances. A P-value < 0.05 was considered statistically significant.

Results

The CV analysis revealed that the PMM of tooth 14 showed the greatest variation at 4 mm (33.95%) and the smallest at 8 mm (18.17%). Overall, the low coefficient of variation indicated high measurement consistency (Supplementary Table 1).

Differences in bilateral PMM

A line graph was plotted based on the average PMM at the measured posterior tooth positions (Fig. 5), showing a generally symmetrical distribution between the same measurement points on both sides of the maxilla. Further analysis using independent sample t-tests revealed no statistically significant differences in PMM between the corresponding points on the left and right sides ($P>0.05$) (Supplementary Table 2).

Differences in PMM at different measurement points of the same tooth position

In the premolar region, PMM initially increases and then decreases as the distance from the gingival margin extends. In contrast, the molar region continuously increases with greater distance from the gingival margin. Variance analysis was employed to examine these differences (Table 1). Since PMM at different measurement points for the same tooth position is inconsistent, the Games-Howell test was further applied for comparison (Supplementary Table 3).

At various tooth positions, PMM generally increased from the lower measurement levels (2–6 mm) to the higher levels (8–14 mm), with specific patterns at each position. At tooth position 14, PMM values were similar at the 2 mm and 4 mm levels ($P>0.05$), increased at the 6 mm level, and were similar from the 8 mm to 14 mm levels ($P>0.05$). At tooth position 24, PMM values increased from the 2 mm to 4 mm levels, then were similar from the 6 mm to 14 mm ($P>0.05$). At tooth position 15, PMM values increased from the 2 mm to 8 mm levels and were similar to the 10 mm to 14 mm ($P>0.05$). At

Table 2 PMM (mm) at the same measurement point across different tooth positions

Distance (mm)	14	15	16	*F*	Distance (mm)	24	25	26	*F*
2	2.02 ± 0.64^{b}	2.18 ± 0.55^{ab}	2.25 ± 0.60^{a}	2.323	2	2.02 ± 0.50^{b}	2.13 ± 0.46^{ab}	2.26 ± 0.57^{a}	3.265
4	2.42 ± 0.82^{a}	2.53 ± 0.63^{a}	2.25 ± 0.60^{a}	2.28	4	2.86 ± 0.78^{a}	2.65 ± 0.08^{ab}	2.49 ± 0.84^{b}	3.455
6	3.35 ± 0.64^{a}	3.19 ± 0.62^{a}	2.46 ± 0.65^{b}	31.674^{***}	6	3.51 ± 0.83^{a}	3.35 ± 0.76^{ab}	2.54 ± 0.86^{b}	22.807^{***}
8	3.83 ± 0.70^{a}	4.01 ± 0.75^{a}	3.01 ± 0.84^{b}	27.730^{***}	8	3.86 ± 0.85^{a}	4.06 ± 0.87^{ab}	3.11 ± 0.85^{b}	19.633^{***}
10	3.98 ± 0.75^{b}	4.50 ± 0.85^{a}	3.58 ± 1.07^{c}	15.137^{***}	10	4.19 ± 0.90^{a}	4.44 ± 0.81^{a}	3.66 ± 0.91^{b}	11.644^{***}
12	4.21 ± 0.89^{a}	4.51 ± 1.07^{a}	4.25 ± 1.26^{a}	1.29	12	4.39 ± 0.95^{a}	4.55 ± 1.00^{a}	4.42 ± 1.08^{a}	0.42
14	4.18 ± 0.93^{b}	4.31 ± 0.97^{b}	5.03 ± 1.35^{a}	10.037^{***}	14	4.42 ± 1.22^{b}	4.47 ± 0.97^{b}	5.28 ± 1.39^{a}	9.193^{**}

The same letters in the same line indicate no significant difference ($P>0.05$), the different letters in the same line indicate the significant difference ($P<0.05$). Significant differences in PMM were observed across different tooth positions at the same measurement point (: $P<0.05$; **: $P<0.01$; ***: $P<0.001$)

Table 3 Comparison of PMM (mm) between different genders

Variables	Distance (mm)	Male	Female	t	*P*
		n = 25	*n* = 32		
I. Premolar	2	1.99 ± 0.48	2.04 ± 0.52	-0.394	0.695
	4	2.87 ± 0.87	2.85 ± 0.73	0.090	0.929
	6	3.60 ± 0.94	3.44 ± 0.74	0.692	0.492
	8	3.98 ± 0.82	3.76 ± 0.87	0.954	0.344
	10	4.41 ± 0.92	4.02 ± 0.85	1.676	0.099
	12	4.62 ± 0.89	4.21 ± 0.97	1.627	0.109
	14	4.74 ± 1.22	4.17 ± 1.17	1.813	0.075
II. Premolar	2	2.06 ± 0.44	2.19 ± 0.47	-1.063	0.292
	4	2.67 ± 0.74	2.63 ± 0.56	0.252	0.802
	6	3.28 ± 0.79	3.39 ± 0.74	-0.533	0.596
	8	3.98 ± 0.81	4.12 ± 0.93	-0.611	0.544
	10	4.50 ± 0.76	4.40 ± 0.85	0.460	1.165
	12	4.73 ± 0.83	4.42 ± 1.11	1.165	0.249
	14	4.85 ± 0.90	4.18 ± 0.93	2.702	**0.009**
I. Molar	2	2.26 ± 0.46	2.27 ± 0.64	-0.062	0.951
	4	2.69 ± 0.88	2.33 ± 0.78	1.595	0.117
	6	2.45 ± 0.83	2.62 ± 0.89	-0.720	0.475
	8	3.06 ± 0.80	3.14 ± 0.90	-0.376	0.708
	10	3.83 ± 0.94	3.53 ± 0.88	1.236	0.222
	12	4.56 ± 1.11	4.31 ± 1.06	0.858	0.395
	14	5.49 ± 1.44	5.13 ± 1.36	0.976	0.333

tooth position 25, PMM values increased from the 2 mm to 6 mm levels and were similar to the 8 mm to 14 mm levels ($P>0.05$). At tooth positions 16 and 26, PMM values were similar at the 2 mm, 4 mm, and 6 mm levels ($P>0.05$) and increased at higher levels.

Differences in PMM for different teeth at the same measurement point

The PMM values of the right and left maxilla were compared using variance analysis to assess differences (Table 2). The analysis revealed that PMM at the same measurement points varies between different tooth positions. To further investigate these differences, the Games-Howell test was applied (Supplementary Tables 4 and 5).

The results indicate that at the 2 mm, 4 mm, and 12 mm levels, PMM is comparable between premolars and molars. At the 6 mm, 8 mm, and 10 mm levels, the second premolar exhibits the greatest thickness, while at the 14 mm level, the first molar is the thickest. Except at the 2 mm, 12 mm, and 14 mm levels, where the first premolar is the thinnest, the first molar consistently exhibits the least thickness at other measurement points.

Differences in PMM between genders

An independent samples t-test revealed a statistically significant difference only at 14 mm from the gingival margin of the second premolar ($P<0.05$), where males exhibited greater PMM than females. For all other tooth positions, no significant gender differences in PMM were observed ($P>0.05$), indicating that gender exerts a relatively minor influence on PMM (Table 3).

Differences in PMM between ages

An independent samples t-test revealed that only a few sites (2 mm at the second premolar and 2 mm, 4 mm at

the first molar) showed no statistically significant differences ($P > 0.05$). At all other sites, the differences were statistically significant ($P < 0.05$), with the PMM in the middle-aged group being greater than that in the young group (Table 4).

Differences between GB and PMM

An independent samples t-test revealed that only the PMM differences corresponding to varying GB at the 2 mm site of the first molar were statistically significant ($P < 0.05$). In contrast, the results at all other sites showed no statistical significance ($P > 0.05$) (Table 5).

Correlation between PBT and PMM

The Pearson correlation test between PBT and PMM indicated that, for most test sites, $P > 0.05$, suggesting a weak basis for correlation. With $0 \leq |r| \leq 0.5$, the results demonstrate a weak correlation between the two variables at the same level (Table 6).

Comprehensive analysis of gender, age, and PBT influences on PMM

For the (I) Premolar, all regression effects of PMM were significant. Age significantly influenced PMM at all distances except 2 mm, while PBT had a significant effect only at 2 mm and 4 mm ($P < 0.05$). For the (II) Premolar, the regression effects were significant at 2 mm, 6 mm, 8 mm, and 10 mm. Gender and PBT significantly influenced PMM at 2 mm, while age significantly impacted PMM at 8 mm and 10 mm ($P < 0.05$). For the I. Molar, significant regression effects of PMM were observed at 8 mm and 10 mm. Both gender and age significantly influenced PMM at these levels ($P < 0.05$) (Supplementary Table 6).

Discussion

Autogenous grafts are widely regarded as the gold standard for soft tissue augmentation [33]. Recent evidence increasingly supports the notion that sufficient soft tissue thickness and an adequate width of keratinized mucosa positively influence aesthetic outcomes and the health and long-term stability of implant-supported restorations [34, 35]. Due to its favorable histological characteristics and the reproducibility of flap harvesting, the maxillary posterior teeth' palatal region has become the primary donor site for autogenous soft tissue grafting [36]. The greater palatine foramen serves as a protective passage for the palatine artery and nerve, necessitating caution to prevent damage during grafting procedures [37, 38]. Monnet-Corti et al. recommend harvesting grafts within 2–12 mm from the gingival margin, noting the palatine artery lies approximately 14.5 mm from the margin at the second molar [39]. This study also revealed that although PMM reached its maximum at 14 mm, avoiding this depth minimized bleeding and postoperative discomfort [12, 40]. Therefore, accurate preoperative PMM assessment was essential for surgical planning, effective

Table 4 Comparison of PMM (mm) across different age groups

Variables	Distance (mm)	Middle-aged	Young	t	*P*
		n = 19	*n* = 38		
I. Premolar	2	2.26 ± 0.59	1.90 ± 0.40	2.451	0.021
	4	3.28 ± 0.72	2.65 ± 0.74	3.117	0.004
	6	4.06 ± 0.76	3.23 ± 0.72	3.957	<0.001
	8	4.47 ± 0.99	3.55 ± 0.56	3.754	0.001
	10	4.81 ± 0.97	3.88 ± 0.69	3.730	0.001
	12	4.96 ± 1.04	4.10 ± 0.77	3.166	0.004
	14	5.02 ± 1.34	4.12 ± 1.04	2.548	0.016
II. Premolar	2	2.29 ± 0.49	2.06 ± 0.43	1.739	0.091
	4	2.96 ± 0.69	2.49 ± 0.56	2.561	0.016
	6	3.69 ± 0.74	3.17 ± 0.72	2.538	0.016
	8	4.49 ± 1.00	3.85 ± 0.72	2.506	0.018
	10	4.76 ± 0.87	4.28 ± 0.95	2.066	0.047
	12	5.01 ± 1.17	4.32 ± 0.83	2.283	0.030
	14	4.85 ± 0.93	4.28 ± 0.95	2.181	0.036
I. Molar	2	2.39 ± 069	2.20 ± 0.49	1.083	0.288
	4	2.71 ± 0.98	2.38 ± 0.74	1.316	0.199
	6	2.99 ± 1.02	2.32 ± 0.68	2.625	0.014
	8	3.60 ± 0.90	2.86 ± 0.71	3.142	0.004
	10	4.18 ± 0.81	3.41 ± 0.86	3.349	0.002
	12	4.96 ± 0.99	4.15 ± 1.03	2.859	0.007
	14	5.82 ± 1.27	5.02 ± 1.39	2.183	0.035

Table 5 Correlation analysis between GB and PMM (mm)

Variables	Distance (mm)	Thin		Thick	t	*P*
		n = 29		*n* = 28		
I. Premolar	2	1.98 ± 0.48	2.06 ± 0.52		0.663	0.510
	4	2.89 ± 0.79	2.84 ± 0.80		-0.243	0.809
	6	3.41 ± 0.81	3.61 ± 0.85		0.93	0.356
	8	3.84 ± 0.87	3.88 ± 0.84		0.171	0.865
	10	4.15 ± 0.77	4.24 ± 1.03		0.367	0.715
	12	4.41 ± 0.89	4.37 ± 1.03		-0.163	0.871
	14	4.47 ± 1.09	4.37 ± 1.35		-0.321	0.750
II. Premolar	2	2.14 ± 0.50	2.12 ± 1.09		-0.142	0.888
	4	2.59 ± 0.63	2.71 ± 0.66		0.709	0.481
	6	3.31 ± 0.82	3.38 ± 0.70		0.373	0.711
	8	4.14 ± 1.00	3.98 ± 0.72		-0.656	0.514
	10	4.51 ± 0.82	4.37 ± 0.80		-0.616	0.540
	12	4.56 ± 1.15	4.55 ± 0.85		-0.04	0.968
	14	4.51 ± 1.01	4.44 ± 0.95		-0.278	0.782
I. Molar	2	2.41 ± 0.60	2.11 ± 0.49		-2.099	0.040
	4	2.64 ± 0.83	2.34 ± 0.83		-1.361	0.179
	6	2.58 ± 1.05	2.50 ± 0.62		-0.357	0.723
	8	3.10 ± 0.94	3.11 ± 0.76		0.051	0.959
	10	3.57 ± 0.93	3.76 ± 0.90		0.775	0.442
	12	4.33 ± 1.16	4.51 ± 1.00		0.624	0.535
	14	5.16 ± 1.53		5.42 ± 1.25	0.704	0.484

Table 6 Correlation analysis between PBT and PMM (mm)

	Variables	Distance (mm)	PBT				
			2	4	6	8	10
PMM	I. Premolar	2	0.341**	0.391**	0.369**	0.330*	0.230
		4	0.345**	0.480**	0.374**	0.341**	0.230
		6	-0.065	0.152	0.274*	0.260	0.199
		8	0.025	0.013	0.164	0.184	0.098
		10	0.037	0.035	0.128	0.157	0.118
	II. Premolar	2	0.286*	0.267*	0.237	0.207	0.107
		4	-0.039	-0.127	0.219	0.22	0.117
		6	0.148	0.061	0.261*	0.276**	0.307**
		8	-0.142	-0.027	0.16	0.212	0.208
		10	-0.054	-0.005	0.123	0.134	0.128
	I. Molar	2	0.138	0.316*	0.257	0.236	0.206
		4	-0.070	0.167	0.187	0.169	0.140
		6	-0.157	0.035	0.233	0.221	0.213
		8	-0.070	-0.099	0.137	0.228	0.172
		10	-0.092	-0.041	0.174	0.150	0.137

Significant correlations were observed between PBT and PMM (: $P < 0.05$; **: $P < 0.01$; ***: $P < 0.001$)

patient communication, and achieving optimal healing outcomes.

When comparing PMM at the same level across tooth positions, premolars and molars showed similar thickness at the 2 mm, 4 mm, and 12 mm levels. At 6 mm, 8 mm, and 10 mm, the second premolar had the greatest thickness, while the first molar was thickest at 14 mm. These findings aligned with previous studies, indicating that the palatal mucosa was thickest in the premolar region [8], where PMM thickened before thinning, while it continuously thickened in the first molar region [41]. This pattern was likely associated with the course of the greater palatine neurovascular bundle. At the 2 mm level, the average PMM for all tooth positions measured less than 2.5 mm, limiting the suitability of indirect grafting methods [42]. Notably, the PMM from the first premolar to the first molar exceeded 3 mm at distances of 8 mm to 14 mm, supporting the feasibility of both direct and indirect approaches. Direct harvesting ensured the acquisition of at least a 1 mm graft while preserving 0.5 mm of

residual tissue to cover the wound, facilitating optimal postoperative primary healing.

This study also found that, apart from the first premolar being the thinnest at the 2 mm, 12 mm, and 14 mm levels, the thinnest site at other levels was consistently the first molar. This could be attributed to the thicker palatal root of the first molar and the frequent occurrence of verrucous proliferations on the palatal alveolar bone, which may pose challenges for graft harvesting [43]. Based on these measurements, this study recommends the first and second premolar regions as suitable sites for soft tissue graft procedures. Consistent with findings from other studies in the literature, 100% of patients can yield a 5 mm-wide connective tissue graft, and 93% can yield an 8 mm graft [39].

Our study identified a statistically significant gender difference in PMM exclusively at the 14 mm level of the second premolar, with males exhibiting greater thickness. No significant differences were observed at other tooth positions. Although Karadag et al. [44] and Schacher et al. [45] reported thinner mucosa in females, the majority of studies, including ours, found no significant correlation between gender and PMM [42]. Furthermore, our findings demonstrated that PMM increases with age, with age exerting a more substantial influence on PMM than gender, consistent with previous research [8, 46]. In addition to the previously mentioned factors such as increased adipose content, the thickening of PMM may be attributed to the fact that the hard palate mucosa is an orthokeratinized epithelial layer that becomes thicker with age. Aging is also associated with changes in gingival tissue, which is known to become coarser and denser.

The concept of GB, introduced by Ochsenbein C and Ross S in 1969 [47], characterized the soft tissue and alveolar bone influenced by genetic and environmental factors. Using a 1 mm threshold, this study differentiated between thick and thin GB [20, 32]. Research identified thinner PMM in maxillary anterior teeth with a narrow biotype [48], while reports indicated a correlation between LMM and PMM, with thinner biotypes associated with gingival recession [49]. Interestingly, a negative correlation was demonstrated between LMM and underlying bone thickness in the anterior region, 2 mm apical to the cemento-enamel junction [20]. Researchers observed a 1 mm increase in peri-implant PMM when PBT exceeded 4 mm, though causality remained unclear [22]. Our study also confirmed a weak correlation between PBT and PMM, underscoring the necessity of considering factors such as gender and age when evaluating PMM.

However, the present study has some limitations. The combined application of CBCT imaging and IOS is unable to differentiate between the epithelial, adipose, and glandular tissues within the palatal masticatory mucosa, nor does it identify the position of the greater palatine neurovascular bundle in the measured region. Only mucosal changes were analyzed, indicating that future studies should integrate histological analysis for a more detailed investigation. Given the inherent limitations in the demographic composition of our study cohort and the methodological constraints on statistical power, the current findings necessitate rigorous validation through larger-scale, multi-ethnic investigations to establish robust empirical evidence for broader generalizability. Another methodological limitation is that this study used CV instead of the intraclass correlation coefficient (ICC), which is the standard method for evaluating intra- and inter-observer reliability. Future research should incorporate ICC to strengthen the validity of reliability assessments. This study did not incorporate the 3D color-coded deviation maps proposed by Kuralt et al. [50], which use threshold-based color coding to distinctly represent varying soft tissue thicknesses, providing clinicians with a "clinically friendly" tool. In future research, we plan to incorporate 3D color-coded maps to further enhance data visualization and clinical applicability.

In conclusion, regarding PMM, the maxillary posterior region demonstrates symmetrical distribution, and the premolar regions appear to be optimal for harvesting soft tissue grafts. PMM shows no significant correlation with gender, GB, or PBT, but it is thicker in the middle-aged group compared to the younger group. Furthermore, clinicians are advised to use CBCT combined with IOS, when available, to assess PMM in the maxillary posterior region in advance, aiding in surgical planning and enhancing doctor-patient communication.

Abbreviations

FGGs	Free gingival grafts
CTGs	Connective tissue grafts
PMM	Palatal masticatory mucosa
PBT	Palatal bone thickness
GB	Gingival biotype
MRI	Magnetic resonance imaging
CBCT	Cone-beam computed tomography
IOS	Intraoral scanning
LMM	Labial masticatory mucosa
CV	Coefficient of variation
ICC	Intraclass correlation coefficient

Supplementary Information

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Supplementary Material 1

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Author contributions
S.S., T.Z., and W.Z. conceptualized the overall strategy. S.S. and T.Z. equally contributed to the clinical translation, implementation, and preparation of the manuscript and figures. Z.G. and L.J. designed and performed the statistical

analyses and manuscript preparation, including text and figures. W.G. and Y.W. provided supervision and wrote and edited the manuscript. All authors have read and approved the final version of the manuscript.

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

Declarations

Ethics approval and consent to participate
The study received approval from the Ethics Committee of School and Hospital of Stomatology, Cheeloo College of Medicine, Shandong University (20200502) and adhered to the principles of the Declaration of Helsinki. All participants provided their informed consent prior to their involvement in the study.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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