Scientific Reports

https://doi.org/10.1038/s41598-026-61875-y

Article in Press

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Received: 22 March 2026

Accepted: 8 July 2026

Published online: 01 August 2026

Cite this article as: Ocak A. & Akyüz M. CBCT-based submandibular fossa depth classification and panoramic fractal dimension analysis in the posterior mandible. *Sci Rep* (2026). https://doi.org/10.1038/s41598-026-61875-y

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CBCT-Based Submandibular Fossa Depth Classification and Panoramic Fractal Dimension Analysis in the Posterior Mandible

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CBCT-Based Submandibular Fossa Depth Classification and Panoramic Fractal Dimension Analysis in the Posterior Mandible

Abstract

Deep concavities of the submandibular fossa (SF) in the posterior mandible substantially increase the risk of lingual cortical plate perforation during implant placement. Although cone-beam computed tomography (CBCT) enables accurate three-dimensional assessment of SF morphology, panoramic radiography remains the most commonly used initial imaging modality. We investigated whether trabecular bone texture on panoramic radiographs, quantified using fractal dimension (FD), is associated with CBCT-measured SF depth.

In this retrospective cross-sectional study, 133 patients with CBCT and panoramic radiographs obtained within 3 months were included. SF depth was classified as Type I (≤2 mm), Type II (2–3 mm), or Type III (>3 mm). On the matching panoramic level, a 20×20-pixel cancellous region of interest was analyzed in ImageJ using box-counting FD. Group comparisons were performed using the Kruskal–Wallis and Mann–Whitney U tests with Bonferroni correction; correlations were assessed using Spearman's rank correlation coefficient ($p < 0.05$).

A total of 229 hemimandible measurements were evaluated. Mean age was 41.96±15.59 years; 57.1% were female. Mean SF depth was 1.845±0.750 mm and mean FD was 1.0964±0.0667. Median FD was 1.0747, 1.1324, and 1.1340 in Types I, II, and III, respectively (Kruskal–Wallis $p=4.45\times10^{-5}$). FD was significantly higher in Types II and III versus Type I ($p=0.000514$ and $p=0.00633$), with no difference between Types II and III ($p=1.00$). SF depth positively correlated with FD (Spearman rho=0.4138, $p=6.95\times10^{-11}$).

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Panoramic FD values reflected CBCT-defined SF depth categories, with deeper concavities showing consistently higher trabecular texture complexity. These results suggest that SF anatomical variation is a previously unrecognized source of regional FD heterogeneity in the posterior mandible and should be considered when interpreting panoramic FD in this region. FD is not proposed as a substitute for CBCT, but as a complementary quantitative descriptor with implications for both surgical risk awareness and radiographic research methodology.

Keywords: cone-beam computed tomography, fractal dimension, panoramic radiography, submandibular fossa, trabecular bone

Introduction

The posterior mandible exhibits substantial inter-individual anatomical variability, particularly on its lingual aspect, where the submandibular fossa (SF) forms a concavity below the mylohyoid line that accommodates the submandibular gland. The depth of this concavity ranges from a barely perceptible flattening to a pronounced lingual undercut, and several CBCT-based studies have documented this variability in different populations. [1-5, 13, 17] Although the SF has traditionally been described in the context of surgical anatomy — specifically in relation to the risk of lingual cortical plate perforation during implant osteotomy, which may cause vascular injury, floor-of-mouth bleeding, and airway compromise [2, 14, 15] — its broader biological significance has received comparatively little attention. Specifically, whether SF morphology reflects or is accompanied by changes in the microarchitecture of the overlying trabecular bone has not been systematically examined.

Trabecular bone in the posterior mandible is a dynamic tissue whose architecture adapts to local mechanical and biological stimuli in accordance with Wolff's law. [20] Regional differences in cortical thickness, loading patterns, and adjacent soft-tissue

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relationships may all influence trabecular organization. A deeper SF implies a thinner lingual cortical plate and a different geometric relationship between the submandibular gland, cortex, and cancellous compartment, which raises the possibility that mandibles with pronounced lingual concavities may also display distinct trabecular microarchitectural features in the immediately overlying region. Understanding this relationship is important not only from a surgical perspective but also methodologically: if posterior mandibular FD values are partly determined by the underlying SF morphology, then anatomical variability of the lingual concavity may represent an unrecognized source of heterogeneity in studies using FD as an outcome measure.

Fractal dimension (FD) analysis of panoramic radiographs provides a quantitative, non-invasive measure of trabecular bone structural complexity. It has been applied across a range of clinical contexts, including osteoporosis and antiresorptive drug exposure, periodontal disease, tobacco use, sleep bruxism, hypodontia, post-radiotherapy changes, and peri-implant bone remodeling. [6-12] Across this literature, FD is interpreted as a sensitive surrogate of trabecular complexity that responds to systemic and local biological influences. However, the extent to which regional anatomical variation — independent of disease — contributes to FD values in the posterior mandible has not been examined. Panoramic visibility of the SF has been studied as a qualitative sign associated with CBCT-measured depth [5, 16], but quantitative texture analysis of the overlying bone has not been performed.

To our knowledge, no previous study has directly correlated CBCT-measured SF depth with panoramic FD values of the overlying trabecular bone in the same individuals. We therefore classified SF depth on CBCT and quantified trabecular bone texture via FD analysis on matching panoramic radiographs, testing whether these two variables are associated. A secondary question was whether panoramic FD can provide a quantitative radiographic cue

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before CBCT is obtained. The null hypothesis was that CBCT-measured SF depth and panoramic FD are not significantly associated.

Results

A total of 133 patients were included. The mean age was 41.96 ± 15.59 years (median 42, range 18–73). There were 76 females (57.1%) and 57 males (42.9%). Intraobserver reliability was excellent for SF depth measurements (ICC = 0.983; 98.3%) and good for FD measurements (ICC = 0.760; 76.0%). At the measurement/hemimandible level, age was comparable across SF depth types, with median IQR values of 42 [27.5–55] years in Type I (n=151), 44 [30–57] years in Type II (n=61), and 40 [23–55] years in Type III (n=17), showing no significant difference (Kruskal–Wallis, p=0.572). Consistently, age was not associated with FD (Spearman's, p=0.961, n=229). In contrast, gender distribution differed significantly across SF types (Chi-square test (χ^2), p=0.00686), with an increasing proportion of males from Type I (57/151, 37.7%) to Type II (29/61, 47.5%) and Type III (13/17, 76.5%), indicating that the observed association was largely driven by the higher male representation in the deepest SF category (**Table 1**). Of the 133 patients, 96 (72.2%) had bilateral measurements available, while 25 (18.8%) had right-side only and 12 (9.0%) had left-side only measurements. At the hemimandible level, a total of 229 values were evaluated, comprising 121 right-sided (52.8%) and 108 left-sided (47.2%) measurements. Dentition status at the hemimandible level was dentate in 141 (61.6%) and edentulous in 88 (38.4%) cases. The mean SF depth was 1.845 ± 0.750 mm (median 1.80, range 0.10–4.60), and the mean FD was 1.0964 ± 0.0667 (median 1.1031, range 0.8615–1.2164). FD did not differ significantly by dentition status (dentate vs. edentulous; Mann–Whitney U, p=0.160). SF depth also did not differ significantly between dentate and edentulous measurements, although a borderline trend toward deeper fossae in dentate subjects was observed (Mann–Whitney U, p=0.054). According to SF depth, observations were classified as Type I (≤2 mm,

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n=151), Type II (2–3 mm, n=61), and Type III (>3 mm, n=17), with median SF depths of 1.50 mm, 2.40 mm, and 3.40 mm, respectively. Median FD values were 1.0747 in Type I, 1.1324 in Type II, and 1.1340 in Type III, demonstrating a significant difference across SF types (Kruskal–Wallis, $p=4.45\times10^{-5}$). Bonferroni-adjusted post-hoc comparisons showed that FD was significantly lower in Type I than in Type II (p_adj=0.000514) and Type III (p_adj=0.00633), whereas Type II and Type III did not differ (p_adj=1.00). SF depth was positively correlated with FD (Spearman's, $p=6.95\times10^{-11}$) (**Table 2**).

To address potential gender confounding, additional analyses were performed. The positive SF depth–FD correlation remained significant in both males (n=99, Spearman rho=0.4621, $p=1.47\times10^{-6}$) and females (n=130, rho=0.3265, p=0.000150). In rank-based partial correlation analysis, the association also remained significant after adjustment for gender alone (rho=0.3977, $p=4.25\times10^{-10}$) and after adjustment for gender, age, and dentition status (rho=0.3924, $p=7.57\times10^{-10}$). In a patient-clustered GEE model, SF depth remained independently associated with FD ($\beta=0.03484$, SE=0.00512, $p=1.03\times10^{-11}$), whereas gender was not an independent predictor ($\beta=0.00488$, p=0.583).

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Discussion

Panoramic FD values of the posterior mandibular trabecular bone were significantly higher in deeper CBCT-defined SF concavities, with clear differences between Type I and the deeper Type II–III categories. This shows that the SF is not merely a surface anatomical landmark, but is accompanied by a measurable difference in the structural complexity of the trabecular bone immediately overlying it. To our knowledge, no prior study has reported this anatomical–microarchitectural association in the posterior mandible.

Several biological mechanisms may underlie this association. A deeper lingual concavity is associated with a thinner lingual cortical plate and an altered geometric

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relationship between the cortex, cancellous compartment, and adjacent submandibular gland. In such mandibles, the trabecular network may reorganize to compensate for reduced cortical support and altered local loading, producing a more heterogeneous and branching architecture that yields higher FD values. This interpretation is consistent with the broader principle that trabecular bone adapts to local mechanical demand in accordance with Wolff's law, [20] and complements previous FD studies that have shown trabecular complexity to be sensitive to systemic and local biological influences. [6-12] However, an alternative explanation is equally important: because the SF is a concavity and panoramic radiography is a two-dimensional projection, higher FD values in deeper concavities may partly reflect superimposition, altered projection geometry, or local contrast effects rather than true histological complexity. Therefore, the present results should be interpreted as a radiographic texture association, not as direct proof of increased three-dimensional trabecular complexity. Histomorphometric validation would be required to confirm the biological basis.

Previous studies have focused predominantly on the visibility or linear depth of the SF on two-dimensional and three-dimensional imaging, without addressing whether morphological differences are accompanied by changes in the surrounding trabecular tissue. Sümer et al. found no significant correlation between panoramic radiolucent visibility of the SF and CT-measured depth [16], while Keşkek et al. reported that visible fossae tended to be anatomically deeper. [5] The present study moves beyond subjective visibility assessment to a quantitative texture-based approach: FD captures a structural property of the bone itself, and this property differs significantly between shallow and deep SF categories.

The anatomical–microarchitectural association identified in this study also has methodological implications for the broader FD literature. Posterior mandibular FD has been used as an outcome measure in studies of osteoporosis, periodontitis, bruxism, hypodontia, and post-radiotherapy bone. [6-12] If regional FD values are partly determined by the

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underlying SF morphology, then anatomical variability of the lingual concavity may act as an unrecognized confounder in such studies, particularly when samples differ in sex distribution or SF depth characteristics. Awareness of this association is therefore relevant whenever FD is measured in the posterior mandibular region, regardless of the specific clinical question.

CBCT remains the reference standard for three-dimensional mandibular assessment, and FD was not intended to replace it. Rather, the goal was to characterize the trabecular textural correlate of an anatomical feature that has otherwise been described only in geometric terms. CBCT depicts three-dimensional shape; panoramic FD quantifies two-dimensional textural complexity of the same region. These two measures are therefore complementary. In routine clinical workflows, panoramic FD might serve as a preliminary quantitative cue during review of panoramic images before CBCT is obtained — particularly in retrospective or research contexts — but it should not guide surgical planning without CBCT confirmation.

To address potential gender confounding, additional sex-stratified and multivariable analyses were performed. The proportion of males increased with deeper SF categories, with Type III showing a clear male predominance (76.5%), consistent with previous CBCT-based reports. [3, 5, 13, 18] The SF depth–FD correlation remained significant separately in males (rho=0.4621, $p=1.47\times10^{-6}$) and females (rho=0.3265, p=0.000150), and after adjustment for gender, age, and dentition status (partial Spearman rho=0.3924, $p=7.57\times10^{-10}$). In the patient-clustered GEE model, SF depth remained an independent predictor of FD (β=0.03484, SE=0.00512, $p=1.03\times10^{-11}$), whereas gender was not independently associated with FD (p=0.583). The SF depth–FD association therefore cannot be attributed solely to the higher proportion of males in the deeper SF categories.

The absence of a significant difference between Type II and Type III warrants careful interpretation. The Type III subgroup was small (n=17), which substantially reduces statistical power for pairwise post-hoc comparisons. In addition, Type III was predominantly male

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(76.5%), and gender distribution differed significantly across SF categories. These factors may have contributed to the apparent plateau between Type II and Type III. Therefore, while the difference between shallow (Type I) and deeper concavities (Types II–III) is supported by the current data, the distinction between moderate and severe concavities requires validation in larger samples with more balanced gender distribution.

Dentition status was not significantly associated with SF depth in our sample, though a borderline trend toward deeper fossae in dentate subjects was observed (p=0.054). This contrasts with some earlier reports; differences in study design and population composition likely explain the discrepancy. Regarding edentulous regions, post-extraction bone resorption and functional atrophy may influence FD values even when the mandibular canal and inferior cortical border are used as references, and this should be considered in future studies.

Limitations

This study has several limitations. First, the retrospective single-center design and use of a single imaging device limit generalizability. Second, FD analysis is inherently ROI-dependent; the 20×20-pixel ROI was chosen to avoid the mandibular canal, roots, and cortical borders in a narrow anatomical region, but larger ROIs may capture broader trabecular complexity and should be compared in future sensitivity analyses. Third, panoramic images were exported as JPEG files because TIFF-format archives were not available retrospectively; compression artifacts may have affected pixel-level texture. Fourth, matching the CBCT deepest SF point to the panoramic image was based on anatomical landmarks rather than exact three-dimensional co-registration, so residual localization error is possible. Fifth, measurements were performed by a single observer; intraobserver reliability was assessed (ICC=0.760 for FD, indicating moderate/good reproducibility) but interobserver reliability was not evaluated. Sixth, 96 patients contributed bilateral observations, creating clustered data; a patient-clustered GEE sensitivity analysis was therefore included. Seventh, the Type

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III subgroup was small (n=17) with a high male proportion, so further validation in larger balanced samples is required.

Methods

Study design

This retrospective, cross-sectional study was conducted in accordance with the ethical principles of the Declaration of Helsinki. The study protocol was approved by the Non-Invasive Clinical Research Ethics Committee of Erzincan Binali Yıldırım University (approval no: 2026-01/05; date: 08/01/2026). CBCT images were retrieved from the archives of the Department of Dentomaxillofacial Radiology, Faculty of Dentistry, Erzincan Binali Yildirim University. The CBCT dataset included scans acquired between January 2024 and November 2025, which had been obtained for routine clinical indications (e.g., evaluation of impacted teeth, orthodontic treatment planning, and implant assessment). Only patients who also had a panoramic radiograph obtained within the 3 months preceding the CBCT acquisition date were included. The exclusion criteria comprised images of non-diagnostic quality, scans exhibiting developmental defects or pathologies (e.g., cysts, tumors, fractures) in the region of interest. An a priori sample size calculation for the primary correlation analysis was performed using a two-tailed test ($\alpha = 0.05$) and 80% power, assuming an expected effect size of $r = 0.25$. The required minimum sample size was 124 participants. After applying the inclusion and exclusion criteria to all eligible CBCT examinations, 133 patients were included in the final analysis, exceeding the minimum requirement.

Image Acquisition and Analysis

All CBCT images were acquired using a Planmeca ProMax® 3D Classic unit (Planmeca, Helsinki, Finland) with standardized parameters: 90 kVp, 6.3 mA, an acquisition time of 12.1 seconds, and an 8x8 cm field of view (FOV). This FOV was selected to capture

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the bilateral posterior mandible in a single acquisition for the majority of patients; in cases where bilateral anatomy could not be captured in one scan, only the side adequately covered was evaluated. The voxel size was set to 200 μm with a slice thickness of 0.2 mm. Following acquisition, the raw data were exported in DICOM format for analysis. Radiographic evaluation was performed using the Weasis DICOM Viewer (Roduit N. Weasis DICOM viewer. v4.6.6. https://github.com/nroduit/Weasis) on a 24-inch Dell LCD monitor (Dell Inc., TX, USA) with a resolution of 1920 × 1080 pixels. Images were initially displayed at the default window/level settings of the Weasis viewer for this device (Window: 4094 / Level: 1048); per-case brightness and contrast adjustments were applied as needed to optimize cortical border visibility. Images were assessed by a single oral and maxillofacial radiologist (A.O.) with 10 years of clinical experience. Intraobserver reliability was evaluated by repeating all measurements on a randomly selected subset of 30 hemimandibles at least two weeks after the initial assessment. Agreement was quantified using the two-way mixed-effects intraclass correlation coefficient (ICC) with absolute agreement based on single measures.

CBCT measurement of SF depth

The volumes were reoriented by aligning the mandibular plane (defined by the menton and bilateral gonion points) parallel to the horizontal plane. Cross-sectional images were then reconstructed perpendicular to the mandibular alveolar ridge at a slice thickness and interval of 1 mm. Although the native voxel size was 0.2 mm, 1 mm reconstruction intervals were intentionally selected to provide standardized cross-sections that reduce slice-to-slice variability and improve consistency in identifying the deepest SF concavity, in accordance with common practice in CBCT-based mandibular morphometric studies. For each hemimandible, the CBCT slice displaying the deepest submandibular fossa concavity was selected. SF depth was then measured as the perpendicular distance from the deepest point of the concavity to a tangent line connecting the most superior and most inferior outer margins

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of the depression. The greatest depth recorded for each fossa was used for classification, and SFs were grouped into three categories according to Parnia and Sadik [1, 4]: Type I (≤ 2 mm), Type II (2–3 mm), and Type III (> 3 mm) **(Fig. 1)**.

Panoramic FD analysis

Panoramic radiographs were acquired using a ProMax (Planmeca, Helsinki, Finland) device and exported in JPEG format. JPEG compression was applied at the highest quality setting available on this unit; while JPEG encoding can introduce minor pixel-level artifacts, the image quality was visually assessed as adequate for trabecular bone texture analysis, which relies on relative density variations rather than absolute pixel values. FD calculation was performed using ImageJ v1.54d, a public domain software developed by the National Institutes of Health (Bethesda, MD, USA). After measuring the maximum depth of the submandibular fossa (SF) on CBCT images, the anatomic level of this measurement was identified for each hemimandible. This anatomic level was then localized on the corresponding panoramic radiograph by matching stable mandibular landmarks (e.g., the mandibular canal course, mental foramen region, inferior cortical border, and the relative position and distance to adjacent tooth roots) to ensure that the panoramic assessment represented the same SF region evaluated on CBCT. In edentulous regions, localization relied primarily on the mandibular canal trajectory and the inferior cortical border as reference structures. Following level matching, a standardized square region of interest (ROI) measuring 20 × 20 pixels was placed on the panoramic image within the trabecular bone area corresponding to the SF projection, ensuring that the ROI remained entirely within cancellous bone and away from adjacent cortical structures, tooth roots, and the mandibular canal. This ROI size was selected based on prior dental fractal analysis studies using equivalent or smaller ROIs and is appropriate for the spatial scale of trabecular bone texture visible in

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panoramic radiographs at this magnification. Care was taken to avoid inclusion of the dense inferior cortical border, the mandibular canal lumen, and any visible artifacts. The ROI was positioned to best represent trabecular bone texture while maintaining consistent placement criteria across all cases. To calculate FD of the trabecular bone structure, the ROIs were submitted to a sequence of processing steps following the method described by White and Rudolph. [19] First, the ROI image was duplicated and subjected to Gaussian blurring (sigma=35 pixels) to eliminate fine and medium-scale brightness variations. The blurred image was then subtracted from the original, and a value of 128 was added to the resulting pixels to discriminate bone marrow spaces from trabeculae. The resulting image was automatically binarized using the same ImageJ command and settings for all ROIs; no manual threshold adjustment was performed. To reduce noise, the binary image underwent sequential erosion and dilation. The image was then inverted to ensure the trabeculae were black and the marrow spaces were white. Finally, the image was skeletonized. The FD of the resulting skeletonized image was calculated using the "Fractal Box Counting" function in ImageJ **(Fig. 2)**.

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Statistical Analysis

Continuous variables were summarized as mean ± standard deviation (SD), median, and minimum–maximum values, while categorical variables were reported as frequencies and percentages. The normality of continuous variables was assessed using the Shapiro–Wilk test. As the main quantitative variables (SF depth and FD) did not meet normality assumptions, non-parametric tests were used. Specifically: (1) comparisons of FD and SF depth between two independent groups (e.g., dentate vs. edentulous, male vs. female) were performed using the Mann–Whitney U test; (2) comparisons of FD and age across the three SF depth types (Type I, II, III) were conducted using the Kruskal–Wallis test with Bonferroni-adjusted post-hoc pairwise comparisons; (3) associations between categorical variables (e.g., gender

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distribution across SF types) were evaluated using the chi-square test; and (4) the correlation between SF depth and FD was assessed using Spearman's rank correlation coefficient. To address potential gender confounding, additional analyses were performed: (1) sex-stratified Spearman correlations between SF depth and FD, (2) rank-based partial correlation controlling for gender, age, and dentition status, and (3) a patient-clustered generalized estimating equation (GEE) model with patient ID as the clustering variable, including SF depth, gender, age, and dentition status as independent variables and FD as the dependent variable. A second GEE model used SF type (with Type I as reference). Intraobserver reliability for both SF depth and FD measurements was quantified using the two-way mixed-effects ICC with absolute agreement. All analyses were performed in SPSS (Version 26; IBM Corp., Armonk, NY, USA) with a significance level of $p < 0.05$.

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Conclusion

CBCT-measured SF depth was significantly associated with panoramic FD in the posterior mandible, with deeper concavities (Types II and III) showing higher trabecular texture values than shallow ones (Type I), indicating that panoramic FD reflects differences in underlying SF morphology. Since panoramic radiography is universally accessible in routine dental practice, FD analysis may serve as a preliminary quantitative cue about SF depth during routine radiographic review, potentially prompting earlier consideration of cross-sectional imaging. SF morphological variation should also be recognized as a potential confounder in posterior mandibular FD studies. CBCT remains the gold standard for accurate SF depth assessment, and FD is not proposed as its substitute. Future prospective studies with larger, more diverse samples are needed to establish clinical thresholds before this approach can be recommended for routine preoperative screening.

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Abbreviations

CBCT: Cone-Beam Computed Tomography

DICOM: Digital Imaging and Communications in Medicine

FD: Fractal Dimension

FOV: Field of View

ICC: Intraclass Correlation Coefficient

IQR: Interquartile Range

JPEG: Joint Photographic Experts Group

kVp: Kilovolt peak

mA: Milliampere

ROI: Region of Interest

SD: Standard Deviation

SF: Submandibular Fossa

SPSS: Statistical Package for the Social Sciences

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Acknowledgements

Not applicable.

Author contributions

A.O. conceived and designed the study, performed CBCT and panoramic image analysis, interpreted results, and drafted the manuscript. M.A. contributed to study design,

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performed statistical analysis, and critically revised the manuscript. All authors read and approved the final manuscript.

Ethics approval and consent to participate

This retrospective study was conducted in accordance with the Declaration of Helsinki and was approved by the Non-Invasive Clinical Research Ethics Committee of Erzincan Binali Yıldırım University (approval no: 2026-01/05; date: 08/01/2026). As this study used archived radiographic records and involved no direct patient contact, the requirement for informed consent was waived by the ethics committee.

Consent for publication

Not applicable.

Data availability

The datasets used in this study are not publicly available due to patient privacy and institutional restrictions, but may be obtained from the corresponding author upon reasonable request.

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Competing interests

The authors declare that they have no competing interests.

Funding

The authors received no specific funding for this work.

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Tables

Table 1. Age and gender distribution across submandibular fossa depth types.

	Type I (n=151)	Type II (n=61)	Type III (n=17)	p-value
Age (Median)	42	44	40	0.572*
Male, n (%)	57 (37.7%)	29 (47.5%)	13 (76.5%)	0.007**
Female, n (%)	94 (62.3%)	32 (52.5%)	4 (23.5%)	

SF, submandibular fossa; SF types using the Kruskal–Wallis test (p*>0.05). Gender distribution Chi-square test. (p** < 0.05).

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Table 2. Submandibular fossa depth types and corresponding fractal dimension values at the measurement.

SF Type	n (measurements)	SF depth, median [IQR] (mm)	FD, median	Post-hoc (Mann–Whitney, Bonferroni p_adj)
Type I (≤2 mm)	151	1.50 [1.15–1.80]	1.0747	vs Type II: 0.000514*; vs Type III: 0.00633*
Type II (2–3 mm)	61	2.40 [2.20–2.60]	1.1324	vs Type I: 0.000514*; vs Type III: 1.00
Type III (>3 mm)	17	3.40 [3.20–3.50]	1.1340	vs Type I: 0.00633*; vs Type II: 1.00

SF, submandibular fossa; FD, fractal dimension; IQR, interquartile range; Mann–Whitney U tests with Bonferroni adjusted p-values indicates statistically significant difference.($p^* < 0.05$)

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Figure legends

Fig. 1 CBCT cross-sectional images illustrating the technique used to measure SF depth, with examples of Type I, Type II, and Type III concavities.

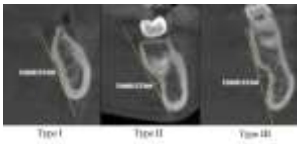
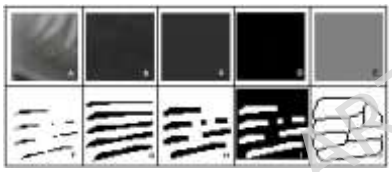


Fig. 2 Fractal dimension measurement steps in ImageJ; (A) ROI selection; B) duplicated image; (C) blurred with a Gaussian filter; (D) addition of 128 gray values to each pixel; (E) binarized into a two-color image; (F) eroded; (G) dilated; (H) inverted; (I) skeletonized.



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