

Morphometric Analysis of Mandibular Canal Variations Using CBCT and Its Clinical Implications in Implant Dentistry: A Cross-Sectional Study

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ABSTRACT

Background

Precise three-dimensional assessment of the mandibular canal is essential before posterior mandibular implant placement because variations in canal course, terminal branching, and proximity to the alveolar crest may increase the risk of inferior alveolar nerve injury.

Methods

This cross-sectional cone-beam computed tomography (CBCT) study evaluated 240 mandibular scans of adults aged 20-70 years. Bilateral measurements were made at the second premolar, first molar, and second molar regions. Canal-to-crest distance, canal-to-buccal cortex distance, canal diameter, anterior loop length, bifid canal prevalence, and implant-related risk zones were recorded. Interobserver reliability was assessed using intraclass correlation coefficients.

Results

The mean age was 42.8 ± 12.6 years, with 126 males (52.5%) and 114 females (47.5%). Mean canal-to-crest distance reduced posteriorly from 17.64 ± 2.92 mm at the second premolar to 13.21 ± 2.76 mm at the second molar ($p < 0.001$). The mandibular canal was positioned significantly closer to the buccal cortex in the second molar region (4.18 ± 1.06 mm) than in the premolar region (5.62 ± 1.21 mm; $p < 0.001$). An anterior loop was detected in 34.6% of patients, with a mean length of 2.36 ± 0.91 mm. Bifid mandibular canal was observed in 14.2% of patients, most commonly the retromolar type. High-risk implant zones, defined as canal-to-crest distance < 10 mm or anterior loop > 3 mm, were identified in 19.6% of scans.

Conclusion

CBCT demonstrated clinically relevant mandibular canal variations that may alter implant length, angulation, and safety margins. Routine preoperative CBCT interpretation should include systematic mapping of the canal, anterior loop, and accessory branches before implant surgery.

Keywords

mandibular canal; cone-beam computed tomography; dental implants; anterior loop; bifid mandibular canal; inferior alveolar nerve.

INTRODUCTION

Dental implant rehabilitation in the posterior mandible is strongly influenced by the spatial relationship between the residual alveolar ridge and the mandibular canal. The canal contains the inferior alveolar neurovascular bundle, and inadvertent violation during osteotomy preparation or implant insertion may result in altered sensation, pain, dysesthesia, paraesthesia, or medicolegal complications. Conventional two-dimensional radiographs provide valuable screening information, but they are limited by magnification, superimposition, and inability to depict the buccolingual position of the canal. Cone-beam computed tomography (CBCT) has therefore become an important three-dimensional imaging tool for implant planning when proximity to vital structures is suspected [1].

Consensus recommendations for implant imaging emphasize that CBCT should be justified according to clinical need and optimized to obtain adequate diagnostic information at the lowest reasonable radiation exposure [2]. In posterior mandibular implant dentistry, this justification is commonly met when the available bone height is uncertain, when the mandibular canal is poorly visualized on panoramic radiographs, or when ridge resorption suggests reduced vertical clearance. CBCT allows multiplanar reconstruction, curved panoramic reformats, and cross-sectional evaluation, enabling the clinician to measure residual bone height and width more accurately than with two-dimensional imaging [3].

The mandibular canal does not follow a uniform

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linear course. Its position may change from lingual to buccal direction as it approaches the mental foramen, and its vertical relation to the alveolar crest varies with age, sex, dentition status, ethnicity, and alveolar resorption. Studies of mandibular vital structures have highlighted the importance of assessing the canal, mental foramen, mandibular incisive canal, and anterior loop before implant surgery [4,5]. These structures are particularly important in the premolar and molar regions, where implant planning often requires balancing prosthetic position against a safe distance from the canal.

The anterior loop of the inferior alveolar nerve is a terminal configuration in which the neurovascular bundle extends anterior to the mental foramen before curving posteriorly to exit through it. Its reported prevalence and length vary widely due to differences in population characteristics, imaging modality, voxel size, and diagnostic criteria. CBCT-based studies have shown that the anterior loop is clinically relevant for interforaminal and premolar implant placement because reliance on the mental foramen alone may underestimate the true anterior extension of the nerve [6,7]. Accordingly, a fixed universal safety distance may not be adequate for all patients.

Another clinically significant variation is the bifid mandibular canal, which may present as retromolar, dental, forward, or buccolingual canals. Such accessory canals may carry neurovascular branches and may be associated with inadequate local anesthesia, unexpected bleeding, or nerve irritation during mandibular surgery. Earlier panoramic studies reported low prevalence, whereas CBCT studies have identified higher detection rates because three-dimensional imaging improves visualization of accessory canals [8,9]. Systematic reviews also indicate that prevalence estimates are strongly influenced by imaging method, with CBCT detecting variations more frequently than panoramic radiography [10].

Recent CBCT studies have documented the morphology of the mandibular canal, mental foramen, anterior loop, and accessory foramina in different populations [11,12]. However, population-specific morphometric data remain relevant because mandibular canal dimensions and positions show ethnic and anatomical variability. In implant dentistry, the clinical value of CBCT lies not merely in detecting the canal but in converting radiographic findings into practical surgical decisions, including implant length selection, need for

short implants or guided surgery, avoidance of high-risk trajectories, and preservation of a minimum safety zone.

Despite the availability of CBCT, many reports focus on isolated variants such as the anterior loop or bifid canal. Fewer cross-sectional studies combine canal position, canal diameter, buccolingual course, anterior loop morphology, bifid canal pattern, and implant-related risk categorization within the same dataset. This integrated approach may be more useful for clinicians because implant planning requires simultaneous assessment of vertical, horizontal, and anatomical-risk parameters. Therefore, the present study aimed to evaluate mandibular canal variations using CBCT and determine their clinical implications for implant planning in the posterior mandible. The objectives were to measure canal-to-crest and canal-to-cortex distances at standardized sites, assess anterior loop and bifid canal prevalence, examine age- and sex-related differences, and categorize implant-related anatomical risk zones.

MATERIALS AND METHODS

Study design and setting: This observational cross-sectional study was conducted using archived CBCT scans obtained from patients referred to the Department of Oral and Maxillofacial Radiology and Implant Dentistry for diagnostic or implant-related assessment. The study period was January 2024 to December 2025. All scans had been acquired for clinical reasons, and no additional radiation exposure was performed for the purpose of this study.

Sample size: The sample size was calculated using an expected mandibular canal variation prevalence of 20%, a 95% confidence level, and 5% absolute precision. The minimum required sample was 246 hemi-mandibles. To improve precision and allow subgroup analysis, 240 patient scans representing 480 hemi-mandibles were included.

Inclusion criteria: CBCT scans of adults aged 20-70 years with complete visualization of the mandible from the mandibular ramus to the symphysis were included. Scans were eligible when the mandibular canal could be traced on both sides, the field of view included the mandibular premolar and molar regions, and image quality was adequate for measurement.

Exclusion criteria: Scans were excluded if they showed mandibular fracture, cystic or neoplastic lesion

involving the canal, previous mandibular reconstructive surgery, severe motion artefact, extensive metallic artefact obscuring the canal, impacted teeth directly superimposed on the measurement region, or congenital craniofacial deformity. Completely edentulous mandibles with severe ridge collapse that prevented standardized reference-point identification were also excluded.

CBCT acquisition protocol: Images were obtained using a standardized CBCT protocol with 90 kVp, 8-10 mA, 12 x 8 cm field of view, voxel size of 0.2 mm, and exposure time adjusted according to manufacturer recommendations. DICOM data were reconstructed using dedicated implant-planning software. Multiplanar views were aligned so that the occlusal plane was horizontal and the mandibular arch was traced using curved planar reconstruction.

Measurement protocol: Measurements were recorded bilaterally at three sites: second premolar, first molar, and second molar regions. At each site, the shortest vertical distance from the superior border of the mandibular canal to the alveolar crest was measured. The buccal and lingual cortical distances were measured from the canal wall to the respective cortices. Canal diameter was measured in the coronal plane at the widest internal canal outline. When the anterior loop was present, its length was measured from the anterior-most extension of the canal loop to the anterior border of the mental foramen on reconstructed panoramic and axial views. Bifid canals were classified as retromolar, dental, forward, or buccolingual according to their course.

Implant-related risk categorization: A hemi-mandible was categorized as low risk when canal-to-crest distance was ≥ 12 mm with no anterior loop greater than 3 mm and no accessory canal in the implant site. Moderate risk was defined as canal-to-crest distance of 10-11.9 mm, anterior loop of 2-3 mm, or canal positioned < 4 mm from either cortical plate. High risk was defined as canal-to-crest distance < 10 mm, anterior loop > 3 mm, bifid/accessory canal crossing a potential implant site, or canal diameter > 3.5 mm with reduced residual bone height.

Reliability assessment: Two calibrated observers independently evaluated 40 randomly selected scans. Measurements were repeated after two weeks. Intraobserver and interobserver reliability were assessed using intraclass correlation coefficients for continuous measurements and Cohen's kappa for categorical

variables.

Statistical analysis: Data were entered into Microsoft Excel and analyzed using SPSS version 27.0. Continuous variables were expressed as mean \pm standard deviation. Categorical variables were expressed as frequency and percentage. Paired t-test compared right and left sides. Independent t-test compared sex-based differences. One-way analysis of variance with Bonferroni post hoc testing compared measurement sites and age groups. Chi-square test assessed associations between anatomical variations and categorical variables. A p-value < 0.05 was considered statistically significant.

RESULTS

A total of 240 CBCT scans were included, representing 480 hemi-mandibles. The mean age of the participants was 42.8 ± 12.6 years. The study population included 126 males (52.5%) and 114 females (47.5%). The 31-50-year age group formed the largest subgroup (44.6%). Interobserver reliability was excellent for canal-to-crest distance (ICC=0.91), canal diameter (ICC=0.88), and anterior loop length (ICC=0.86). Agreement for anterior loop detection and bifid canal classification was substantial, with kappa values of 0.82 and 0.79, respectively.

The mean canal-to-crest distance showed a significant progressive reduction from the second premolar region to the second molar region ($p < 0.001$). The mean value was 17.64 ± 2.92 mm at the second premolar, 15.18 ± 2.71 mm at the first molar, and 13.21 ± 2.76 mm at the second molar. The canal was also closer to the buccal cortex posteriorly, with the buccal cortical distance decreasing from 5.62 ± 1.21 mm at the second premolar to 4.18 ± 1.06 mm at the second molar ($p < 0.001$). Canal diameter was greatest in the molar region, with a mean of 2.71 ± 0.49 mm at the second molar.

Sex-based comparison showed that males had significantly greater canal-to-crest distances than females at all measured sites. At the first molar region, males showed a mean canal-to-crest distance of 15.82 ± 2.68 mm compared with 14.47 ± 2.59 mm in females ($p < 0.001$). However, bifid canal prevalence and anterior loop prevalence did not differ significantly between males and females.

Anterior loop was detected in 83 patients (34.6%) and 139 hemi-mandibles (29.0%). The mean anterior loop length was 2.36 ± 0.91 mm, with 21 hemi-mandibles

(4.4%) showing a loop length greater than 3 mm. Bifid mandibular canal was observed in 34 patients (14.2%) and 46 hemi-mandibles (9.6%). Retromolar canal was the most common type (52.2%), followed by forward canal (23.9%), dental canal (15.2%), and buccolingual canal (8.7%).

Implant-related risk categorization identified 230 hemi-mandibles (47.9%) as low risk, 156 (32.5%) as moderate risk, and 94 (19.6%) as high risk. High-risk classification was most frequent in the second molar region and in patients older than 50 years. The most common causes for high-risk classification were reduced canal-to-crest distance <10 mm (11.9%), anterior loop >3 mm (4.4%), and accessory canal intersecting a potential implant trajectory (3.3%).

Table 1. Demographic distribution and CBCT scan characteristics of the study population

| Variable | Category | n | % / Mean ± SD |
|-----------------|----------------------|-----|---------------|
| Age (years) | Overall | 240 | 42.8 ± 12.6 |
| Age group | 20-30 years | 48 | 20.0% |
| Age group | 31-50 years | 107 | 44.6% |
| Age group | 51-70 years | 85 | 35.4% |
| Sex | Male | 126 | 52.5% |
| Sex | Female | 114 | 47.5% |
| Evaluated sides | Right hemi-mandibles | 240 | 50.0% |
| Evaluated sides | Left hemi-mandibles | 240 | 50.0% |
| Voxel size | CBCT protocol | 240 | 0.2 mm |

Table 2. Morphometric measurements of the mandibular canal at different mandibular regions

| Measurement site | Canal-to-crest distance (mm) | Buccal cortical distance (mm) | Lingual cortical distance (mm) | Canal diameter (mm) | p-value |
|------------------|------------------------------|-------------------------------|--------------------------------|---------------------|---------|
| Second premolar | 17.64 ± 2.92 | 5.62 ± 1.21 | 3.84 ± 0.96 | 2.31 ± 0.42 | <0.001 |
| First molar | 15.18 ± 2.71 | 4.76 ± 1.14 | 4.18 ± 1.02 | 2.54 ± 0.46 | <0.001 |
| Second molar | 13.21 ± 2.76 | 4.18 ± 1.06 | 4.61 ± 1.08 | 2.71 ± 0.49 | <0.001 |

Table 3. Prevalence of mandibular canal variations and implant-related risk categorization

| Parameter | Patient-level prevalence | Hemi-mandible prevalence | Mean dimension | Clinical implication |
|--------------------------|--------------------------|--------------------------|----------------|--|
| Anterior loop present | 83/240 (34.6%) | 139/480 (29.0%) | 2.36 ± 0.91 mm | Premolar implant safety margin required |
| Anterior loop >3 mm | 19/240 (7.9%) | 21/480 (4.4%) | 3.48 ± 0.31 mm | High-risk interforaminal/premolar planning |
| Bifid mandibular canal | 34/240 (14.2%) | 46/480 (9.6%) | - | Accessory neurovascular pathway |
| Retromolar canal type | 24/46 sides | 24/46 (52.2%) | - | Risk during posterior implant flap/osteotomy |
| Low-risk implant anatomy | - | 230/480 (47.9%) | - | Routine safety margin adequate |
| Moderate-risk anatomy | - | 156/480 (32.5%) | - | Shorter implant/guided planning advisable |
| High-risk anatomy | - | 94/480 (19.6%) | - | Altered implant length, angulation, or site required |

DISCUSSION

The present CBCT-based cross-sectional study demonstrated clinically relevant variations in mandibular canal morphology and position. The principal findings were that the vertical distance from the canal to the alveolar crest decreased posteriorly, the canal assumed a more buccal position in the second molar region, anterior loop was present in approximately one-third of patients, and bifid mandibular canal was detected in 14.2% of patients. These findings support the view that implant planning in the mandible should be individualized rather than based solely on assumed average anatomy.

The observed reduction in canal-to-crest distance from premolar to molar regions is clinically important. Posterior mandibular implants frequently require adequate vertical bone height to maintain a safe distance from the inferior alveolar nerve. In the current study, the second molar region showed the least available vertical clearance, which may explain why this area more commonly entered the moderate- or high-risk category. Earlier anatomical reviews emphasized that mandibular canal position and residual bone height

must be evaluated together during implant treatment planning [13]. Our data extend this concept by showing site-specific morphometric values that can guide implant length and angulation.

The buccolingual position of the mandibular canal also has practical significance. In our sample, the canal was closer to the buccal cortex in posterior molar regions. This may increase the risk of canal proximity when implants are placed in a buccally directed trajectory to accommodate prosthetic emergence or ridge morphology. CBCT recommendations for implant dentistry highlight the value of cross-sectional imaging when implant placement is close to vital structures because two-dimensional imaging cannot reliably reveal buccolingual anatomy [14]. The findings of this study reinforce that canal mapping should include buccal and lingual distances, not only vertical bone height.

Anterior loop prevalence in the present study was 34.6% at the patient level, with a mean length of 2.36 mm. This falls within the broad range reported in CBCT studies and is consistent with the concept that the anterior loop cannot be reliably predicted clinically. Apostolakis and Brown used CBCT to evaluate the anterior loop and recommended caution during interforaminal implant planning because loop length shows marked individual variation [15]. Similarly, studies from different populations have reported variable prevalence and dimensions of the anterior loop, indicating that population-based averages should not replace patient-specific CBCT assessment [16].

The clinical implication of anterior loop detection is most relevant for implants in the mandibular premolar region. A planned osteotomy placed anterior to the mental foramen may still encroach upon the loop if the clinician assumes that the nerve exits directly at the foramen. In our sample, 4.4% of hemi-mandibles had anterior loop length greater than 3 mm, and these were classified as high risk. This finding supports the practice of marking the anterior border of the loop during digital implant planning and maintaining a safety zone beyond the visible loop when selecting implant length and position.

Bifid mandibular canal was identified in 14.2% of patients in this study. Naitoh et al. described CBCT-based classification of bifid canals and reported that CBCT detects such variations more effectively than panoramic radiography [17]. Subsequent studies and reviews have confirmed that bifid canal prevalence varies according

to method and diagnostic criteria, with CBCT revealing more accessory canals than conventional imaging [18]. The retromolar canal was the most frequent subtype in our dataset, which is relevant to posterior implant surgery, flap design, and harvesting procedures in the retromolar region.

Although a bifid canal may not always alter implant position, it should alert clinicians to the possibility of accessory neurovascular contents. Accessory canals crossing potential osteotomy paths may increase the risk of bleeding or postoperative sensory disturbance. In addition, canal branching may explain unexpected local anesthesia failure. Therefore, implant-planning reports should describe not only the main inferior alveolar canal but also accessory branches near the proposed implant site.[19-22]

Sex-based analysis showed that males had greater canal-to-crest distances than females at all measured sites. This may be related to larger mandibular dimensions and differences in alveolar bone height. However, sex did not significantly influence the prevalence of anterior loop or bifid canal in the present study. This suggests that while linear dimensions may vary by sex, anatomical variants remain sufficiently unpredictable to require direct imaging assessment in both males and females.

The risk categorization used in this study was designed to translate CBCT observations into clinical decision-making. Nearly one-fifth of hemi-mandibles were classified as high risk. This does not imply that implants are contraindicated, but rather that modifications may be necessary. Options include shorter implants, narrower implants, ridge augmentation, altered implant angulation, use of static or dynamic guided surgery, or selection of an alternative prosthetic design. In cases with limited canal-to-crest distance, maintaining at least a 2 mm safety distance from the canal is generally considered prudent, although additional caution is necessary where imaging quality, drill length, or surgical access is compromised.

The main strength of this study is its integrated assessment of mandibular canal position, canal diameter, anterior loop, bifid canal, and implant-related risk in the same cohort. The use of standardized measurement sites and reliability assessment improves reproducibility. However, limitations must be acknowledged. The study was conducted using archived scans from patients referred for diagnostic or implant-related evaluation,

which may introduce selection bias. Functional outcomes such as postoperative neurosensory changes were not assessed because the study was radiographic. Also, although CBCT improves three-dimensional visualization, very small accessory canals may remain difficult to detect in the presence of noise or artefact.

Future research should combine CBCT-based morphometry with actual implant-planning software simulations and postoperative outcomes. Automated segmentation and artificial intelligence-based canal tracing may improve consistency, but such approaches require validation across scanners, voxel sizes, and populations before routine clinical use. Until then, careful manual review by trained clinicians remains essential.

Overall, the findings indicate that CBCT provides clinically actionable information for implant dentistry when interpreted systematically. A structured reporting approach should include canal-to-crest distance at proposed implant sites, buccolingual canal position,

canal diameter, anterior loop length, mental foramen location, and accessory canal presence. Such reporting can reduce anatomical uncertainty and support safer mandibular implant placement.

CONCLUSION

This cross-sectional CBCT study demonstrated significant morphometric variation in the mandibular canal, with reduced canal-to-crest distance in posterior molar regions and a more buccal canal position toward the second molar area.

Anterior loop and bifid mandibular canal were common findings and created clinically relevant risk zones for implant placement, especially in the premolar and posterior mandibular regions.

Preoperative CBCT interpretation in implant dentistry should include systematic evaluation of canal position, anterior loop length, accessory canal morphology, and residual bone dimensions to support safe implant selection and surgical planning.

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