Khalij Libya Journal of Dental and Medical Research. 2026;10(4):381-389
https://doi.org/10.47705/kjdmr.26410
eISSN:2708-888X

Original article

Safe Zone Mapping in the Anterior Mandible for Implant Osteotomy: Insights from a Cone Beam Computed Tomography Study

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Abstract
Surgical procedures involving dental implant placement in the anterior mandible may place adjacent neurovascular structures, particularly the inferior alveolar nerve and its anterior loop, at risk of injury. This study aimed to evaluate the anatomical relationships between the genial tubercle (GT), mental foramen (MF), and anterior loop (AL) using cone-beam computed tomography (CBCT). The dimensions of the crestal surgical safe zone and variations according to sex and side were also investigated. A retrospective CBCT-based study was conducted using 712 scans. After applying predefined exclusion criteria, 200 scans with a clearly identifiable anterior loop were randomly selected, including 100 males and 100 females (mean age: 44.5 years). Bilateral measurements included the distances from the GT to the MF, from the GT to the AL, and the corresponding crestal safe zone. Statistical analyses were performed to assess sex-related differences, side-specific variations, and the distribution of safe-zone categories. All morphometric parameters were significantly greater in males than in females. Mean GT-MF distances were 28.11 ± 2.60 mm and 27.38 ± 2.40 mm on the right and left sides in males, compared with 26.63 ± 1.55 mm and 26.22 ± 2.12 mm in females. The mean crestal safe zone measured 24.62 mm (right) and 23.78 mm (left) in males, and 21.66 mm (right) and 20.55 mm (left) in females. Right-sided GT-AL and safe-zone measurements were significantly greater than left-sided values in both sexes. Most males (66%) were classified within the 20-25 mm safe-zone category, whereas 58% of females were grouped within the 15-20 mm category. The anterior mandibular interforaminal region exhibits significant sexual dimorphism and bilateral asymmetry. Patient-specific CBCT assessment is essential for safe implant planning and minimizing neurovascular complications.
Keywords. *Cone-beam Computed Tomography, Anterior Loop, Inferior Alveolar Nerve.*

Received: *02/09/26*
Accepted: *30/10/26*
Published: *10/11/26*

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Introduction

The inferior alveolar nerve (IAN), a terminal branch of the mandibular nerve, courses within the mandibular canal and divides at the mental foramen (MF) into the mental and incisive branches [1,2]. The mental nerve provides sensory innervation to the skin and mucosa of the lower lip and chin, whereas the incisive nerve continues anteriorly through the incisive canal within the interforaminal region to supply the anterior mandibular teeth [3]. Several studies have reported that the MF is most commonly located in the region of the second premolar [1,4,5]. However, using the MF as the sole anatomical landmark for surgical interventions in the mandibular region may be inadequate. In some individuals, the IAN extends anterior to the MF before looping superiorly and posteriorly to exit through the foramen. This anatomical configuration is known as the anterior loop (AL) of the inferior alveolar nerve. The prevalence and extent of the AL exhibit considerable variability among individuals and may be influenced by factors such as age, sex, and ethnicity [6,7].

Accurate identification of the AL and its anatomical variations is essential for reducing the risk of iatrogenic injury during implant surgery. Previous studies have reported cases of transient sensory disturbances lasting from 3 to 16 months following implant placement procedures [8-10]. Injury to the IAN may result in anesthesia, paresthesia, pain, or a combination of these symptoms, which can adversely affect patients' quality of life. Therefore, current recommendations advocate maintaining a safety margin of 1 to 2 mm from the neurovascular bundle during implant osteotomy planning based on radiographic assessment [11,12]. Determination of a safe implant placement zone can be particularly challenging in edentulous patients because alveolar bone resorption and the loss of conventional anatomical landmarks make orientation more difficult. In such cases, the genial tubercle (GT), a bony prominence located at the mandibular midline on the lingual surface, serves as a stable and reproducible anatomical reference point for morphometric evaluation in both dentate and edentulous individuals [13-16].

Khalij Libya Journal of Dental and Medical Research. 2026;10(4):381-389
https://doi.org/10.47705/kjdmr.26410
eISSN:2708-888X

Conventional two-dimensional imaging techniques often have limited accuracy in detecting and evaluating the AL, which has led to the widespread use of cone-beam computed tomography (CBCT) in preoperative implant assessment. CBCT provides high-resolution three-dimensional visualization of critical osseous and neurovascular structures, thereby facilitating more accurate surgical planning and enhancing patient safety [17-19]. Furthermore, CBCT enables clinicians to determine the appropriate implant dimensions, position, and angulation before surgery [20,21].
To the best of our knowledge, no previous study has evaluated these anatomical landmarks in a Libyan population. Therefore, the present study aimed to establish a reproducible CBCT-based method for measuring the distance between the GT and the AL of the IAN within the interforaminal region of the mandible. Additionally, this investigation sought to contribute to the development of a standardized protocol for defining a safe implant osteotomy zone and minimizing the risk of neurovascular complications during implant placement.

Methods

Sample Size Calculation

Given the considerable variability in the reported prevalence of the anterior loop (AL) among previous international studies [22–24], a sample size of 200 CBCT scans was determined. The required sample size was calculated using a standard sample size calculator to achieve a 5% margin of error at a 99% confidence level.

Source of Data

This retrospective study was conducted using existing CBCT records obtained from a digital imaging archive; no additional radiographic examinations were performed for research purposes. The study sample consisted of 200 subjects referred to the Department of Radiology at Al-Amal Dental Center, Benghazi, Libya, for preoperative dental implant assessment between December 2025 and August 2026. Digital Imaging and Communications in Medicine (DICOM) datasets were exported for radiographic analysis.

Eligibility Criteria

Inclusion Criteria

- Patients aged 18 years or older.
- Fully dentate, partially edentulous, or completely edentulous individuals scheduled for dental implant treatment.
- High-quality CBCT scans encompassing the entire mandibular arch.

Exclusion Criteria

- Presence of congenital syndromes, systemic bone diseases, or a history of previous mandibular surgery.
- History of maxillofacial trauma or mandibular fractures involving the symphyseal or parasymphyseal regions.
- Presence of impacted or supernumerary teeth, or odontogenic lesions/pathologies occupying the interforaminal region.
- CBCT scans affected by motion or metallic artifacts that impaired accurate visualization and measurement of the anatomical structures.

Radiographic Image Acquisition

All CBCT examinations were performed using standardized imaging parameters, including a tube voltage of 110 kV, tube current ranging from 1 to 20 mA, and an exposure time of 40 s. The effective radiation dose was 136 μSv. Cross-sectional images were reconstructed with a slice thickness of 1.0 mm and an inter-slice interval of 1.0 mm. A medium field of view (FOV) measuring 6 × 14 cm was used to include the entire mandibular arch.

Image Analysis and Radiographic Measurements

A comprehensive anatomical assessment was performed using multiplanar reconstructed images, including coronal, sagittal, and panoramic views, in addition to three-dimensional volume-rendered reconstructions. DICOM datasets were imported into Acteon Imaging Suite (AIS) software (Version 4.6.1; Acteon, Mérignac, France) for analysis. Following image segmentation, the "Draw Nerve" tool was used on cross-sectional images to trace the course of the inferior alveolar nerve, its anterior loop, and the mental nerve (Figure 1 & 2).

Identification Criteria for the Anterior Loop (AL)

The anterior loop of the inferior alveolar nerve was identified using multiplanar CBCT assessment (axial, coronal, sagittal, and cross-sectional views). The diagnosis was based primarily on the anatomical course and continuity of the mandibular canal as described in previous CBCT studies [1,3,5,6]. anal Continuity and Anatomical Course: The anterior loop was identified by tracing the mandibular canal anterior to the mental foramen and confirming its posterior curvature and return toward the mental foramen before its emergence. In contrast, the mandibular incisive canal was identified as a continuation of the mandibular canal extending anteriorly beyond the mental foramen without a posterior looping course.

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Multiplanar Verification: Canal continuity was verified in axial, coronal, sagittal, and cross-sectional reconstructions to minimize misinterpretation and ensure accurate differentiation between the anterior loop and the incisive canal.
Radiographic Appearance: When present, the anterior loop appeared as a well-defined corticated neurovascular canal located anterior to the mental foramen. The final diagnosis was based on tracing the canal pathway and confirming its anatomical continuity across multiple imaging planes.

Linear Measurements and Safe Zone Calculation

Reference points were established on the alveolar crest corresponding to the selected anatomical landmarks.

- Reference Lines: Vertical reference lines were projected from the genial tubercle (GT), the anterior border of the mental foramen, and the most anterior extension of the anterior loop.
- Distance Measurements: Linear distances from the GT to each reference landmark were measured bilaterally.
- Safe Zone Calculation: To establish a clinically applicable surgical safety margin, 2 mm were subtracted from the measured GT-to-AL distance on each side independently. This value was considered the available crestal surgical safe zone. All measurements were subsequently verified using axial images to ensure accuracy. (Figure 1 & 2).
- Safe-Zone Categorization: For categorical analysis, the smaller of the right- and left-side safe-zone measurements was used for classification to provide a conservative estimate of the available surgical safe zone. Participants were subsequently categorized into four predefined groups (Categories): (1) 10-15 mm, (2) >15-20 mm, (3) >20-25 mm, or (4) >25 mm.

Measurement Reliability

To eliminate inter-examiner variability, all measurements were performed by a single experienced oral and maxillofacial radiologist. To assess intra-observer reliability, all bilateral measurements were repeated by the same examiner after a predetermined interval under identical viewing conditions.

Ethical Considerations

The study protocol was reviewed and approved by the Ethics Committee of the Faculty of Medicine, University of Benghazi, Libya. Given the retrospective and non-interventional nature of the study and the use of anonymized data, the requirement for written informed consent was waived by the committee.

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics for Windows version 24 (IBM Corp., Armonk, NY, USA). The normality of continuous variables was assessed using the Kolmogorov-Smirnov test. Variables demonstrating a normal distribution were presented as mean ± standard deviation (SD). Comparisons between males and females were conducted using the independent-samples Student's t-test, whereas side-to-side comparisons were performed using the paired-samples Student's t-test. A two-tailed p value < 0.05 was considered statistically significant.

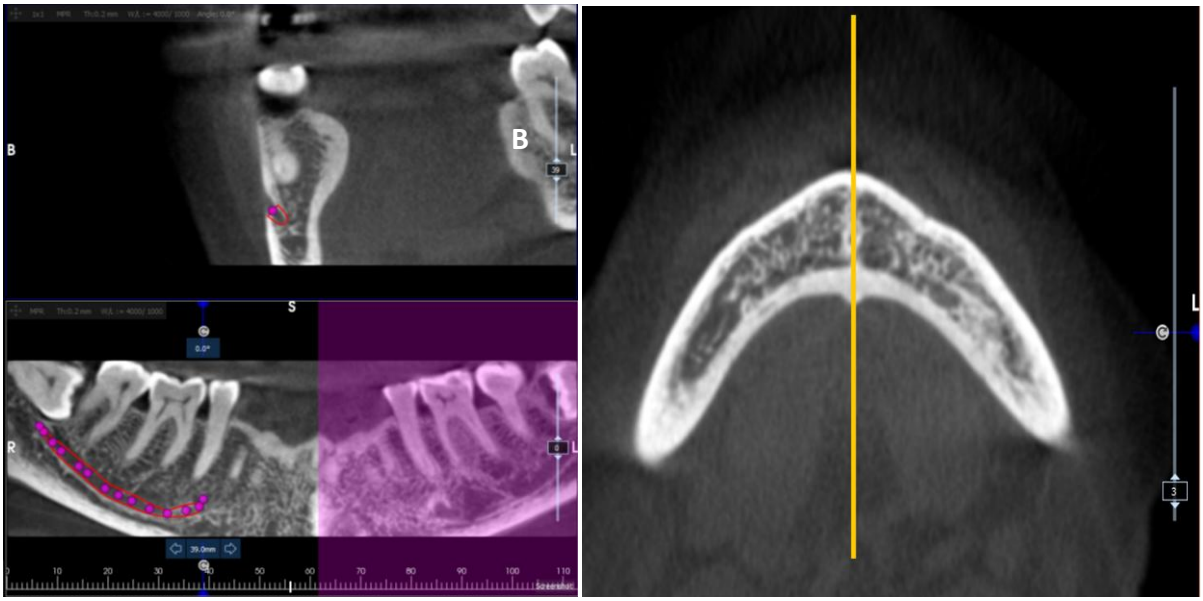


Figure 1. (A) Tracing of the IAN in its canal from the lingula to the mental foramen using nerve drawing tool. (B) A line bisecting the genial tubercle is marked on the axial cut.

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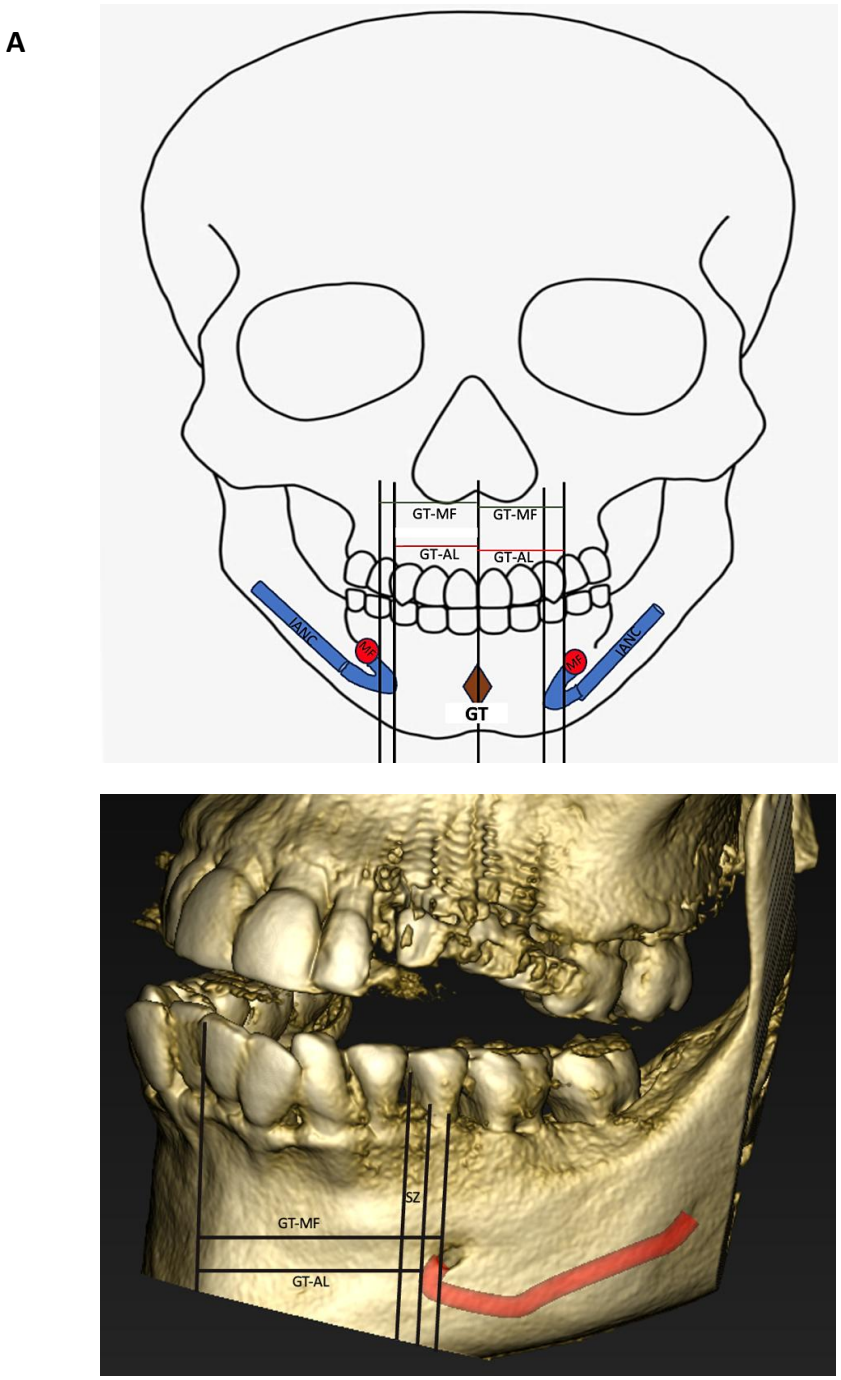


Figure 2. (A) Diagrammatic representation of the various measurements from the genial tubercle (GT), inferior alveolar nerve canal (IANC), mental foramen (MF), to the anterior loop (AL), R: right side; L: left side. (B) The complete nerve overlay on the 3D reconstructed mandible (red line). The corresponding distances measured from reference points on the crestal ridges (measurements in black).

Results

Study Population and Reliability Assessment

A total of 712 CBCT examinations were initially screened. Of these, 415 scans were excluded because no identifiable anterior loop (AL) was detected on either side of the mandible. From the remaining 297 eligible scans exhibiting an AL, 200 subjects were randomly selected for inclusion in the study. The final study population comprised 100 males and 100 females, with an overall mean age of 44.5 ± 14.72 years (range: 18-71 years). Normality testing confirmed that all continuous variables were normally distributed ($p > 0.05$). Intra-examiner reliability for all linear measurements was excellent, with an intraclass correlation coefficient (ICC) ≥ 0.994.

Distance Between Genial Tubercle and Mental Foramen (GT–MF)

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(Table 1) and (Figure 3 A) summarize the GT-MF measurements according to sex and mandibular side.
Male Subjects: The mean GT-MF distance was 28.11 ± 2.60 mm on the right side and 27.38 ± 2.40 mm on the left side.
Female Subjects: Female subjects showed relatively less side-related variation than males for GT-MF measurements of 26.63 ± 1.55 mm on the right side and 26.22 ± 2.12 mm on the left side.
Sex Differences: Males exhibited significantly greater GT-MF distances than females on both sides of the mandible.

Table 1. Mean distribution of GT- to MF, GT - AL, and safe zone in the right & left sides for men, women, and all subjects.

Parameter	Male			Female			All subjects		
	Min	Max	M±SD	Min	Max	M±SD	Min	Max	M±SD
R GT-MF	21.22	41.99	28.11±2.6	18.10	31.40	26.63±1.55	18.10	41.99	27.37± 2.26
L GT-MF	19.2	35.67	27.38±2.4	18.30	32.40	26.22±2.12	18.30	35.67	26.80± 2.33
RT GT-AL	18.99	36.55	26.62±2.46	13.10	30.90	23.66±1.99	14.70	35.36	25.14± 2.68
L GT-AL	16.00	35.36	25.78±2.83	14.70	27.80	22.55±2.45	14.28	33.67	24.17± 3.10
R SZ	16.99	33.88	24.62±2.46	12.10	28.90	21.66 ± 1.99	12.10	33.88	23.14± 2.68
L SZ	14.01	32.06	23.78±2.38	11.70	26.80	20.55 ± 2.45	12.18	31.46	22.17± 3.10

Bilateral Comparison Within Sex Groups

Male Subjects

Paired t-test analysis demonstrated significant bilateral differences for all measured parameters (Table 2). GT-MF Distance: The right-sided GT-MF measurement was significantly greater than the left-sided measurement. GT-AL Distance: A significant right-to-left asymmetry was observed, with larger values on the right side. Surgical Safe Zone (SZ): The safe zone was significantly larger on the right side than on the left side. Overall, all anatomical measurements were significantly greater on the right side of the mandible in male subjects.

Table 2. Comparison of the parameters of both sides in male subjects.

Parameter	Side	N	Mean ± SD.	Mean difference	t	p-value
GT-MF	R	100	28.11± 2.6	0.730	17.22	0.001
	L	100	27.38 ±2.4			
GT-AL	R	100	26.62 ±2.46	0.840	17.67	< 0.001
	L	100	25.78 ±2.83			
SZ	R	100	24.62±2.46	0.840	17.67	< 0.001
	L	100	23.78±2.83			

Female Subjects

A similar anatomical pattern was observed in female subjects (Table 3).
GT-MF Distance: The mean right-sided GT-MF distance (26.63 mm) was slightly greater than the left-sided distance (26.22 mm); however, the difference was not statistically significant ($p = 0.172$). GT-AL Distance: The GT-AL distance was significantly greater on the right side than on the left side ($p < 0.001$). Surgical Safe Zone: A larger mean value was observed on the right side.

Table 3. Comparison of the parameters of both sides in female subjects.

Parameter	Side	N	Mean ± SD.	Mean difference	t	p-value
GT-MF	R	100	26.63±1.55	0.41	0.87	0.172
	L	100	26.22± 2.12			
GT-AL	R	100	23.66± 1.99	1.11	21.658	< 0.001
	L	100	22.55± 2.45			
SZ	R	100	21.66± 1.99	1.11	21.658	< 0.001
	L	100	20.55 ±2.45			

Inter-Sex Comparison of Anatomical Measurements

Independent-samples t-test analysis revealed significantly greater measurements in males than in females across all anatomical parameters ($p < 0.001$).
GT-MF Distance: Males exhibited significantly larger GT-MF distances than females, with mean differences of approximately 1.48 mm on the right side and 1.16 mm on the left side ($p < 0.001$).

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https://doi.org/10.47705/kjdmr.26410
eISSN:2708-888X

GT-AL Distance: GT-AL distances were significantly greater in males than in females on both sides of the mandible ($p < 0.001$).
Surgical Safe Zone: Male subjects demonstrated significantly larger safe zone dimensions than female subjects ($p < 0.001$) (Figure 3: A, B, C).

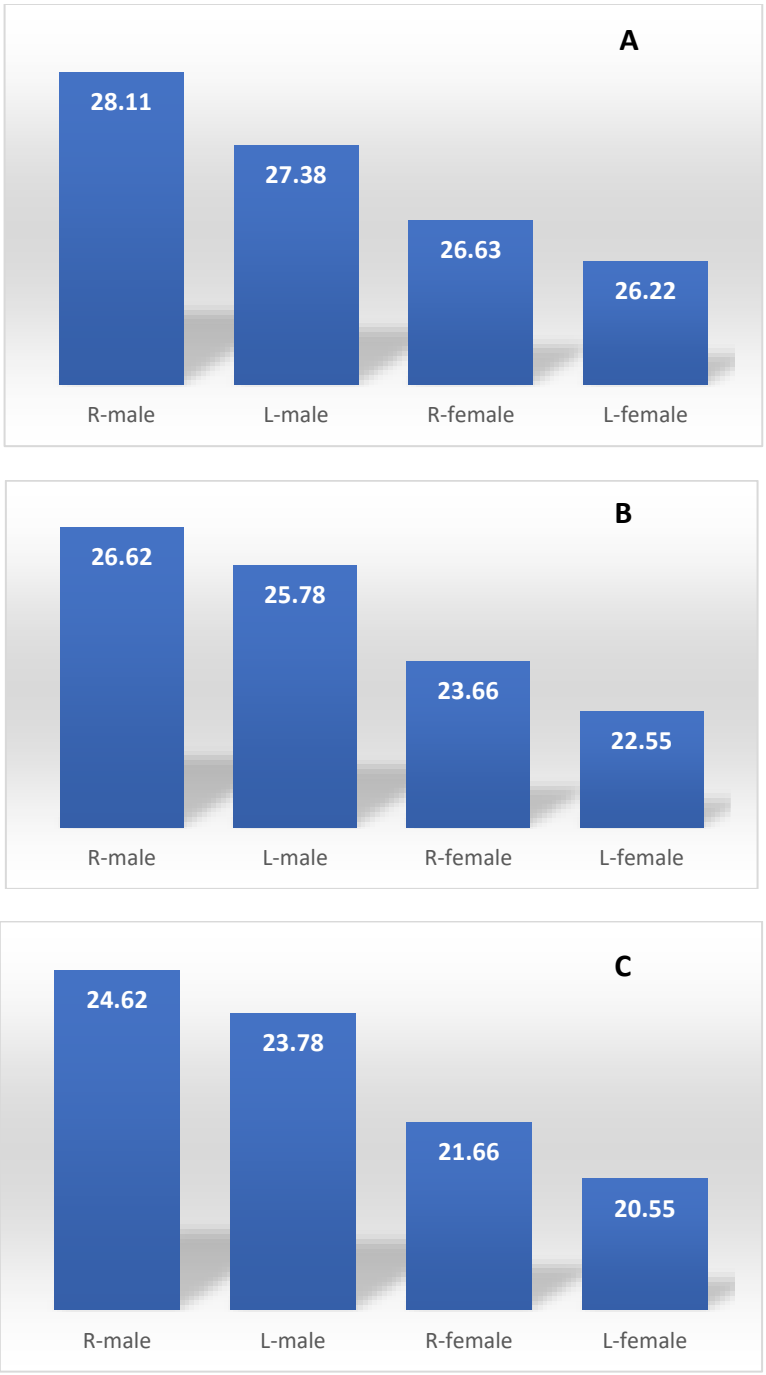


Figure 3. Comparison between right and left, male and female subjects (A) of the GT-MF. (B) of the GT-AL and (C) of the safety zone (SZ).

Surgical Safe Zone Measurements

The dimensions of the surgical safe zone measured from the genial tubercle demonstrated both sexual dimorphism and side-related variation.

- Male Subjects: The mean safe zone measured 24.62 ± 2.46 mm on the right side and 23.78 ± 2.83 mm on the left side. The bilateral difference was statistically significant ($p < 0.001$).
- Female Subjects: Female subjects exhibited smaller mean safe zone dimensions, measuring 21.66 ± 1.99 mm on the right side and 20.55 ± 2.45 mm on the left side. The bilateral difference was statistically significant ($p < 0.001$).

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eISSN:2708-888X

- Sex Differences: The safe zone was significantly larger in males than in females on both sides of the mandible ($p < 0.001$).
- Minimum Safe Zone Dimensions: The minimum safe zone distances observed were:
  - Right side: 16.99 mm in males and 12.10 mm in females.
  - Left side: 14.01 mm in males and 11.70 mm in females.

Categorical Distribution of the Surgical Safe Zone

Categorization of the safe zone dimensions revealed significant differences between males and females ($p = 0.001$) (Table 4).

- Category 1 (10-15 mm): Only three female subjects (3%) were classified within this category, whereas no male subjects were represented.
- Category 2 (15-20 mm): This category included 58% of female subjects compared with only 17% of male subjects.
- Category 3 (20-25 mm): The majority of male subjects (66%) were classified within this category, whereas only 34% of female subjects fell within the same range.
- Category 4 (>25 mm): A safe zone exceeding 25 mm was observed more frequently in males (17%) than in females (5%).

Overall, the categorical analysis further supported the finding that males possessed significantly wider surgical safe zones than females ($p = 0.001$).

Table 4. Safety zone categorization in males and females.

Category	Male	Female	Total	P value
Category 1: 10 < 15mm	0 (0%)	3 (3%)	3	0.001
Category 2: 15< 20mm	17 (17%)	58 (58%)	75	
Category 3: **20** < 25	66 (66%)	34 (34%)	100	
Category 4: > **25**	17 (17%)	5 (5%)	22	
Total	100	100	200	

Discussion

The inferior alveolar nerve (IAN) is recognized as the nerve most frequently affected during oral surgical procedures, accounting for approximately 64.4% of reported nerve injuries, followed by the lingual nerve at 28.8% [7]. Damage to these nerves during implant placement may result in persistent neurosensory disturbances, with long-term complications reported in 7% to 10% of cases [6]. Such injuries may negatively affect quality of life by causing altered sensation of the lower lip and chin, speech difficulties, accidental lip biting, and impaired salivary control. The complex anatomy of the anterior mandible contributes substantially to the risk of surgical complications. Previous investigations have shown a higher frequency of unsafe implant placement in the anterior mandible (77%) compared with the anterior maxilla (58%) [8]. Furthermore, marked anatomical variation has been documented among different populations, emphasizing the importance of population-specific morphometric assessments.

The mental foramen (MF) has been extensively investigated because of its clinical significance. It is most commonly located in line with the apex of the second premolar, with reported frequencies ranging from 45.3% to 62.7%. Nevertheless, the occurrence of accessory or multiple mental foramina has also been described, with prevalence rates varying between 1% and 9% [1,5]. In addition, Carruth et al. demonstrated that the position of the MF can be influenced by factors such as age, alveolar bone resorption, dental status, and its relationship to the inferior border of the mandible [13].

Considerable variability has also been reported regarding the length of the anterior loop (AL). Sinha et al. found AL lengths ranging from 1.8 to 4.8 mm [15], whereas Kilic et al. reported a broader range of 1.5 to 6 mm [16]. The greatest AL length documented in the literature was described by Neiva et al., reaching 11 mm [17]. These differences likely reflect population-specific anatomical characteristics, including racial and ethnic variations. Debbarma et al. observed significantly greater AL lengths on the right side compared with the left [11], whereas studies conducted in Mexican and Californian populations reported no significant side-related or sex-related differences [18,19]. Several authors have reported longer AL dimensions in males [15,20], while Suneetha et al. found a higher prevalence of AL among females [21]. The reported prevalence of AL has varied considerably among different populations. Soman et al. documented a prevalence of 4.24% in a Saudi population [22], whereas Rodricks et al. observed a prevalence of approximately 56% [23]. Mukherjee et al. reported an even higher prevalence of 72% in an Indian population from Odisha [24]. These findings further highlight the substantial anatomical diversity that exists among different ethnic and geographic groups.

In the present study, CBCT was used to evaluate the distance from the genial tubercle (GT) to both the AL and MF. Significant sex-related differences were observed. The mean GT-AL distance in males was 26.63 mm on the right side and 26.22 mm on the left side, whereas corresponding values in females were 23.66 mm and 22.55 mm, respectively. These findings are in agreement with those reported by Mhato et al. [25] and are generally greater than those described by Voon and Patil [9], suggesting the presence of regional anatomical variation.

Several studies have attempted to define safe surgical parameters for procedures performed within the interforaminal region. Previous recommendations suggest maintaining a safety margin of at least 4 mm anterior to the MF and more than

https://doi.org/10.47705/kjdmr.26410
eISSN:2708-888X

12 mm above the inferior mandibular border during alveolar surgery, while a distance of up to 9 mm above the inferior border has been proposed for genioplasty procedures [7,26].

The present findings demonstrated significantly larger safe zones in males than in females. Mean safe-zone values measured 24.62 mm on the right side and 23.78 mm on the left side in males, compared with 21.66 mm and 20.55 mm, respectively, in females. Similar observations have been reported in Indian populations; however, the female participants in the present Libyan sample exhibited comparatively larger safe-zone measurements [25]. These findings suggest that greater caution may be required during surgical planning in female patients and in individuals with relatively smaller mandibular dimensions. To facilitate clinical interpretation, safe-zone measurements were classified into four categories: Category 1 (10-15 mm), Category 2 (15-20 mm), Category 3 (20-25 mm), and Category 4 (>25 mm). Most male participants (66%) were classified within Category 3, differing from previous findings that reported a predominance of males within Category 2 [25]. A substantial proportion of males also belonged to Category 4, further supporting the existence of significant sex-related anatomical differences. The clinical implications of these findings are considerable. Sener et al. recommended maintaining a clearance of at least 2 to 4 mm from critical neurovascular structures during implant site preparation [27]. In full-arch rehabilitation protocols such as All-on-4, implants are frequently placed within the interforaminal region, and posterior angulation of distal implants by approximately 30° to 32° may help avoid damage to vital anatomical structures. Additionally, patients presenting with mandibular deficiencies may require reconstructive procedures, including bone grafting, alloplastic augmentation, or advancement osteotomy techniques [12].

CBCT plays a pivotal role in enhancing surgical safety by enabling accurate visualization of anatomical structures, digital treatment planning, and the fabrication of surgical guides [28]. Koenig et al. highlighted the usefulness of virtual surgical planning in mandibular reconstruction and trauma management, illustrating the broader applicability of CBCT-based workflows for precise surgical interventions [29]. Beyond providing true-size cross-sectional images and multiplanar reconstructions, CBCT offers superior spatial resolution and facilitates accurate linear measurements of the available safe zone before implant placement [28,29]. Compared with conventional panoramic radiography, CBCT has consistently demonstrated superior accuracy in identifying the mandibular canal and mental foramen, largely because two-dimensional imaging is limited by anatomical superimposition, magnification, distortion, and the absence of depth information [4]. Overall, the present findings reinforce the value of CBCT-based morphometric assessment of the anterior mandible. Given the significant variations observed according to sex, side, and population characteristics, individualized preoperative evaluation remains essential for minimizing surgical risk and optimizing treatment outcomes. Clinicians should recognize that anatomical dimensions are influenced by factors such as sex, ethnicity, and alveolar bone resorption and should therefore tailor treatment planning to each patient's specific anatomy.

Limitations

The present study has several limitations. First, the sample consisted of 200 participants recruited from a single institution, which may limit the generalizability of the findings to other populations. Second, variations in tooth inclination and alveolar morphology may have introduced minor measurement inaccuracies during the projection of reference lines from crestal landmarks. Future multicenter studies involving larger and more diverse populations are recommended to validate these findings and further investigate the clinical implications of sex-related anatomical variations in implant dentistry.

Conclusion

This study demonstrated significant anatomical variability and sexual dimorphism in the anterior loop of the inferior alveolar nerve and the available surgical safe zone within the mandibular interforaminal region. Male participants exhibited significantly greater linear measurements and wider crestal safe zones than female participants. In addition, significant bilateral asymmetry was observed, with larger dimensions generally recorded on the right side. These findings underscore the importance of routine preoperative three-dimensional CBCT assessment for the accurate identification of critical anatomical landmarks. Individualized treatment planning based on detailed radiographic evaluation can enhance surgical safety, reduce the risk of neurovascular injury, and improve the predictability of implant-related procedures in the anterior mandible.

Acknowledgment

Special thanks to Mrs. Arwa T. Almajbere, a dental technician at the radiology department, for helpful assistance in gathering and handling the data.

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