



OPEN CBCT based three dimensional odontometric mapping of maxillary anterior teeth in an Indian cohort to guide precision endodontic access cavity preparation

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Access cavity preparation is an important part of endodontic therapy, affecting the effectiveness of canal instrumentation and the durability of the tooth over time. Currently, most access preparation protocols are based on information from a Western population and do not address the anatomical differences of different ethnic groups. This retrospective CBCT study assessed specific odontometric measurements in maxillary anterior teeth—central incisors, lateral incisors and canines—using an Indian population to help identify a clinically relevant and conservative access cavity preparation. A total of six hundred cone-beam computed tomography (CBCT) images of maxillary central incisors, lateral incisors, and canines ($n = 200$ per tooth) were evaluated. Three measurements were made in sagittal view: the distance from the central fossa to the pulp chamber roof (CF–PC), the incisal edge to pulp chamber (IE–PC), and the central fossa to cingulum (CF–C). These images were obtained from Indian individuals aged 18 to 25 years. Differences attributable to sex-based variation, and between teeth, were statistically significant ($p < 0.05$). The lateral incisors had the largest amount of anatomical variability, while the canines had the steepest trajectory of access. These findings provide the first population-based CBCT base-line morphometric values for maxillary anterior teeth in India, and a practical guide to help achieve safe access design that is mindful of tooth anatomy and minimizes the invasiveness of the access.

Keywords Cone-Beam computed tomography, Odontometry, Access cavity preparation, Three-Dimensional imaging, Tooth morphology

The precision of endodontic treatment essentially begins with proper design and execution of the access cavity. This is a critical part of the endodontic treatment that dictates the success of the remainder of the procedures of debridement, shaping of the canals, and obturation. It also has considerable influence over the long-term success of treatment. These include missing canals, over-preparation, perforation, inadequate seal, and ultimately failure¹. While there are common principles established in endodontic access cavity design and execution, advances in technology, materials, treatment philosophies (e.g., minimally invasive endodontics) call for an updated, evidence-based approach to access protocols using imaging and anatomical evidence from today's fields of endodontics and dental/restorative practices².

The maxillary anterior teeth; central incisors, lateral incisors, and canines may differ when it comes to access cavity preparation. While maxillary anterior teeth are less complex than posterior teeth in terms of the canal architecture, they can present unique, anatomical difficulties in root angulation, enamel-dentin thickness, and location of pulp chamber for different ethnic groups^{3,4}.

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Current literature indicates the Indian population displays specific dental morphologies that necessitate separate clinical management^{5,6}. For example, while Western maxillary lateral incisors have variable pulp chamber depths and variability in canal morphology, Indian maxillary lateral incisors were more variable than the standard Western incisor⁷. Additionally, reported variations in maxillary canines despite being a fairly straight forward tooth may have increased curvature, increased depth of pulp chamber and increased enamel thickness can potentially require changes in conventional access⁸. Finally, in addition to the existing anatomic morphometric variations in teeth, there are additional sex differentials that contribute additional complexity to the morphometric and operative access^{9,10}.

Cone-beam computed tomography (CBCT) has dramatically changed dental diagnosis due to three-dimensional, high resolution and multiplanar imaging allowing the clinician to visualize the tooth and surrounding structure and permitting them to do so without overlapping images. CBCT is an excellent tool for endodontic practice as it allows the clinician to see pulp chamber morphology, canal orientation, pericervical dentin thickness, and any anatomical variations that will inform the development of safe and conservative access designs^{11,12}. The use of CBCT is well-supported in the literature in regards to planning and executing both primary and retreatment endodontic cases, especially when anatomical variations will be suspected¹³.

Modern endodontic practice has seen a change in philosophy, of late, rationalizing a more minimally invasive access cavity (MIAC) preparation to preserve tooth structure without compromising the ideal visual and mechanical access to the canal system and subsequent central access instrumentation and debridement. The MIAC paradigm emphasizes preserving the pericervical dentin (PCD), which is the most critical variable for fracture resistance following treatment, as well as longevity of the tooth¹⁴. However, it may lead to a challenge trying to conserve part of the access cavity while properly preparing and imaging the canal, as overly conservative or inaccurate designs could leave an incomplete canal anatomy resulting in insufficient debridement. Therefore, success in MIAC procedures is heavily dependent upon accurate anatomical knowledge and preoperative imaging, which CBCT has the potential to provide¹⁵.

The majority of studies available are aimed at European, North American, or East Asian cohorts and while they can be informative, generalizing for clinical applicability to India is limited with this data¹⁶. Furthermore, no CBCT-based studies on access cavity design come with a standardized, reproducible measurement protocol nor evaluate the clinical significance within minimal intervention practice. The translational gap between morphometric data and clinical protocols also needs to be addressed. The other gap in the literature is the role of anatomical sex differences in access cavity designs. Previous studies indicate that males tend to have larger pulp chambers and dentin thicknesses while females presented narrower root canals and more curvature in specific tooth types when assessing dentin thickness^{17–19}. While these differences may be small in nature, they can contribute to depth and angulation of access cavities more so in the higher risk teeth (e.g., lateral incisors, curved canines). As such, accounting for anatomical sex differences may further enhance planning to more explicitly match treatment strategies.

A case-by-case examination might not adequately address the inherent anatomical complexity found in clinical practice, even though customized preoperative assessment is still a fundamental component of endodontic treatment. Clinicians often underestimate internal morphologic variations; population-based CBCT morphometrics can provide essential reference parameters to guide precision access^{20,21}. Population-based morphometric data provide essential baseline parameters that enhance—not replace—individualized assessment by establishing clinically relevant reference ranges against which deviations can be identified. These normative datasets have already enhanced treatment planning in other dental areas (orthodontics, implantology) by informing diagnostic algorithms, educational modules, and technology-assisted planning systems^{5,6,11}. In endodontics, applying average population-specific measurements from CBCT will improve education, reduce operator variability, improve design consistency in minimally invasive access, and subsequently, reduce complications^{15,22,23}. Therefore, production of high-quality, population-specific morphometric data is scientifically valid and an important strategy for advancing precision-based endodontics moving beyond individual-based assessment.

This study aims to fulfil these unmet needs by performing a complete CBCT-driven odontometric study of maxillary anterior teeth of an Indian population. This study measures three clinically relevant measurements:

- The distance from the central fossa to the pulp chamber (CF-PC),
- The distance from the incisal edge to the pulp chamber (IE-PC), and,
- The distance from the central fossa to the cingulum (CF-C).

These measurements are critical in determining the entry point, angulation, and depth when preparing access cavities. These anatomical landmarks are chosen because they are clinically visible, reproducible between patients, and clinically relevant to where the endodontic files are placed. Beyond measuring population averages, this study also focuses on sex-specific differences and inter-tooth differences (central incisor, lateral incisor, canine) to produce relevant clinical data for clinical applications.

Methodology

Study design and ethical compliance

This research was conducted as a retrospective, cross-sectional imaging analysis using cone beam computed tomography (CBCT), and assessed some odontometric parameters in relation to access cavity preparation in maxillary anterior teeth. The study protocol was reviewed and approved by the institutional ethics committee of the College of Dental Sciences and Hospital (Ref. No. CDSH/Admin/2024; dated 15-10-2024), and was conducted with the full understanding and consent of the ethical principles of the Declaration of Helsinki. In

view of the study's retrospective design and the use of existing anonymised radiographic information, informed consent was not required.

Sample size estimation

Sample size for this study was determined based on the primary outcome, which is the distance from the cusp tip to the furcation; we used an effect size from a previous study. In a previous study²⁴, it reported an effect size of 0.215 for the distance from the cusp tip to the furcation. Therefore, in order to have a statistical power of 0.80 and a significance level of 0.10 our minimum estimated sample size was 534 with GPower (Version 3.1.9.3). In our case, the pilot study used 10% of sample size or 53 samples. In GPower we performed the analysis with a one-tailed test, an effect size (d) 0.2156878, a α error probability of 0.05, a power ($1 - \beta$) of 0.80, and an allocation ratio (N_2/N_1) of 1. The analysis output included a noncentrality parameter (δ) of 2.4921043, a critical t of 1.6477229, 533 degrees of freedom, 534 total sample size, and actual power of 0.8006877. In order to allow a more thorough examination on all the tooth types being studied, the sample was increased to 600 teeth. Each tooth type (the maxillary central incisor, the maxillary lateral incisor, and the maxillary canine) was then represented with a subsample of 200.

Sample selection and imaging protocol

The institutional imaging database was accessed to identify eligible CBCT scans retrospectively. The scans had been originally taken for diagnostic purposes unrelated to the current study velocity during the period January 2022 to December 2023.

Eligibility criteria

- Indian adults aged 18–25 years.
- Permanent maxillary central incisors, lateral incisors, and canines with both good dental morphology, and fully erupted.
- CBCT scans from radiology departments with sufficient resolution and/or diagnostic quality.

Exclusion criteria

- Presence of crown or root fractures, extensive restorative treatment, caries, prostheses, or previous endodontics.
- Evidence of periapical pathology, root resorption, calcified canals and/or severe malalignment.
- CBCT scans with artefacts, insufficient resolution, or data loss.

Imaging parameters

All CBCT scans utilized for this study were taken at the same time, using a standardized imaging protocol, to ensure consistency in the diagnostic protocols and the measurement accuracy. The imaging was performed on a Planmeca ProMax[®] 3D unit (Planmeca Oy, Helsinki, Finland); the images were obtained with a tube voltage of 90 kV, a tube current of 10 mA and an approximate exposure time of 13.8 s, at a Field of View (FOV) of 12 × 15 cm, 16 × 16 cm, with a voxel size of 0.40 mm. The chosen voxel size had enough spatial resolution for our odontometric measures, while keeping patient exposure within guidelines considered diagnostic (2.0–2.2 mGy).

However, given this voxel size, and the ability to measure to the nearest voxel, our smallest reliable unit of measure would be in the submillimeter range. Thus, we defined the threshold for inter-observer variability to be ± 0.2 mm as being clinically relevant variability between measurements - recognizing that there is no way to distinguish reliably at levels smaller than voxel resolution with CBCT. All images were reconstructed in DICOM format, and all measurements were collected using Romexis[®] 3D proprietary software. Each measure was recorded to two decimal spaces to ensure consistent decimal notation.

Odontometric parameters and measurement protocol

Three clinically significant odontometric parameters were measured for each tooth in the sagittal plane, following anatomical standardization:

- CF–PC (Central Fossa to Pulp Chamber Roof): Indicates the vertical penetration depth required to reach the pulp chamber while minimizing over-extension. Aids in controlling bur advancement to avoid floor perforation.
- IE–PC (Incisal Edge to Pulp Chamber Roof): A spatial reference indicating the pulpal entry point of the bur. Also indicates the incisal-pulpal vertical relationship which is critical when choosing the initial angulation for cutting in access preparation of anterior teeth.
- CF–C (Central Fossa to Cingulum): Serves as a spatial reference for modifying bur trajectory in a labio-palatal direction, but also reliably orients bur trajectory to improve any sort of minimally invasive access orientation.

Measuring method

- Identification of the incisal edge, pulp chamber roof, central fossa, and cingulum anatomical landmarks was performed manually, using the sagittal cross-section.
- The software's digital caliper tool allowed for direct linear measurements in millimeters (mm) along a linear vector reflecting the long axis of the tooth.

- All values were recorded to two decimal points (Fig. 1).

Each parameter was measured independently by two calibrated observers. To reduce operator bias, measurements were repeated after a two-week interval for 10% of the sample, and the mean value was used for final analysis.

Observer calibration and reliability measurement

Two endodontists (MK and AMP) with had a formal calibration process, including training on general navigation of CBCT software and identifying anatomical landmarks. They were initially provided with 30 randomly selected scans (that were not part of the final dataset) to use for training before measurements were formally completed.

To ensure reproducibility, each observer completed all parameters individually. Among parameters where there was a discrepancy between observers, ± 0.2 mm was the threshold of acceptable inter-observer variability. Where the discrepancies were beyond that value both observers adjusted the measurements together until there was agreement. This threshold was established based on the voxel resolution (0.40 mm), and on other prior CBCT morphometric studies that would consider any value beyond one sub-millimeter as clinically unimportant variability.

All linear measurements were measured with the digital caliper tool in Romexis[®] 3D (Planmeca, Finland). Each automated measurement was visually checked against established anatomical landmarks in order to guard against becoming too dependent on the software interface. Although no external manual instruments were used, the software-visually integrated workflow provided additional leverage and redundancy against potential misguided identification.

For ambiguous or borderline landmark identifications (e.g., unclear pulp chamber outlines, minimal central fossa depressions, or poor cingulum morphology), multi-planar reconstructions (sagittal, axial, and coronal) were checked. Both study observers independently confirmed the most representative slice in order to document a value, and any ongoing uncertainty was resolved through discussion where necessary.

Reliability testing showed a high level of consistency; inter-observer reproducibility was calculated using Cohen's kappa ($\kappa > 0.85$) and intra-observer reliability was calculated using intraclass correlation coefficients (ICC > 0.90).

Statistical analysis

Data were compiled and examined with the IBM SPSS Statistics (v25.0; IBM Corp., Armonk, NY). Descriptive means, standard deviation (SD), range and 95% confidence intervals were calculated for all odontometric parameters.

For comparison

- Independent samples t-tests were performed to investigate gender-based differences in measurements for each tooth type.

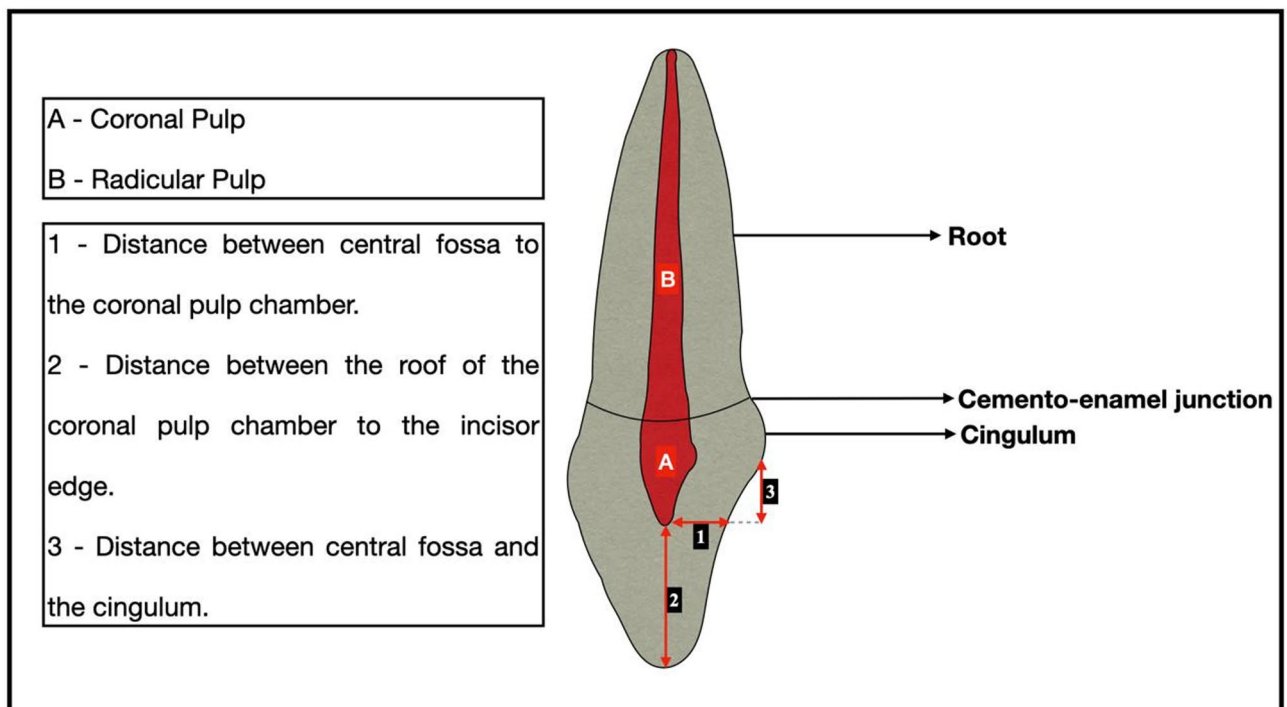


Fig. 1. A schematic representation of the 3 different measurements that were considered for the study.

- Where appropriate, ANOVA or Kruskal-Wallis tests took place to compare values for tooth types (central incisor, lateral incisor, canine).
- A p -value < 0.05 stated statistical significance.

All statistical approaches accounted for all assumptions of normality and homoscedasticity. For datasets that violated normality, or followed non-parametric distributions, non-parametric alternatives were selected instead. Graphical representations of the data, including box plots, were also created to visualise trends in anatomy and potential outliers.

Results

Sample characteristics

In total, 600 maxillary anterior teeth (central incisors, lateral incisors, and canines) scanned from Indian patients aged 18–25 were included in the final analysis. 243 teeth were collected from male patients while 357 were from female patients. All selected scans met the inclusion criteria, and none of the data were omitted as a result of image artifacts or incomplete anatomical view.

Odontometric measurements

Three principal odontometric measurements from this study are illustrated in Fig. 1: CF–PC, IE–PC, and CF–C, were Product examples from the three-dimensional CBCT. While they can be used in application in any clinical access cavity plan, they given their direct measuring of landmark points relevant to clinical purpose of access cavity planning on a maxillary anterior tooth. The CF–PC (Central Fossa to Pulp Chamber Roof) measurement gives the clinician a relevant estimate of vertical depth by demonstrating the distance to achieve penetration to the pulp chamber without compromising the pulpal floor. The IE–PC (Incisal Edge to Pulp Chamber Roof) measurement provides vertical spatial reference and demonstrates the distance from the incisal point of reference to the pulp chamber to guide incisal angulation and entry point during access preparation. The CF–C (Central Fossa to Cingulum) measurement establishes the labio-palatal orientation and therefore guides an ideal axial trajectory of the bur in an indirect manner. This parameter was specifically added to provide an anatomical spatial reference to labio-palatal orientation when the access cavity is being prepared. The CF–C measure is characterized as the linear distance from central fossa—a well-defined occlusal reference location at the deepest part of the central developmental groove—to what is most prominent part of the cingulum area located on the palatal surface. This measure allows clinicians to orient the bur trajectory that aligns to the long axis of the tooth with a minimally invasive approach. The CF–C value will be even more important when external clues, such as restorations, attrition, or developmental variations, can no longer be called upon as reliable references for the access cavity preparation. The CF–C parameter quantifies this anterior-posterior dimension and serves to reproduce consistently access preparation and lessen the chances of removing distal or mesial palatal or labial dentine on the access entry.

The odontometric data collected using sagittal CBCT images of maxillary anterior teeth is displayed in Fig. 2. This figure should be used to provide a visual guide to ensure three main measurements could be repeatedly and consistently identified and recorded: CF – PC (Central Fossa to Pulp Chamber Roof); IE – PC (Incisal Edge to Pulp Chamber Roof); CF – C (Central Fossa to Cingulum). The images (a – i) illustrate the stepwise identification of the anatomical landmarks to take reproducible, standardized measurements.

Table 1 provides mean, standard deviation (SD), and range for the three odontometric parameters and all tooth types. As seen in the three tooth types, there are considerable anatomical differences between the central incisor, lateral incisor, and canine.

Central incisors had the least mean CF–PC distance (2.21 ± 0.37 mm) and the canines had the most CF–PC (3.42 ± 0.85 mm). Central incisors had the largest IE–PC (5.02 ± 0.77 mm) distance compared to the other two tooth types which would equate to deeper penetration of the chamber relative to the incisal edge. The mean CF–C dimension, which indicates the axial buccopalatal angulation difference was most in the central incisor (4.41 ± 0.68) and least in the canine (2.62 ± 0.79 mm) and consistent with their directional difference in morphology. Lateral incisors had the largest standard deviation for all measurements, and this is representative of their variability anatomically in comparison to the central incisor and canine.

Gender differences

Gender comparisons were examined with independent samples t -tests (Table 2). Statistically significant differences were observed in:

- CF–PC and IE–PC values for both central and lateral incisors were significantly greater for males ($p < 0.001$ and $p < 0.05$, respectively).
- CF–C for any tooth type did not have significant differences between genders.

In contrast, canines did not have statistically significant differences based on gender in any of the three dimensions ($p > 0.05$) indicating anatomical symmetry between sexes in these types.

Tooth type comparison

A one-way ANOVA indicated significant differences in all odontometric parameters across tooth types ($p < 0.001$). Post-hoc Tukey testing revealed that (Table 3):

- Canines significantly differed from central and lateral incisors in CF–PC and CF–C distances.

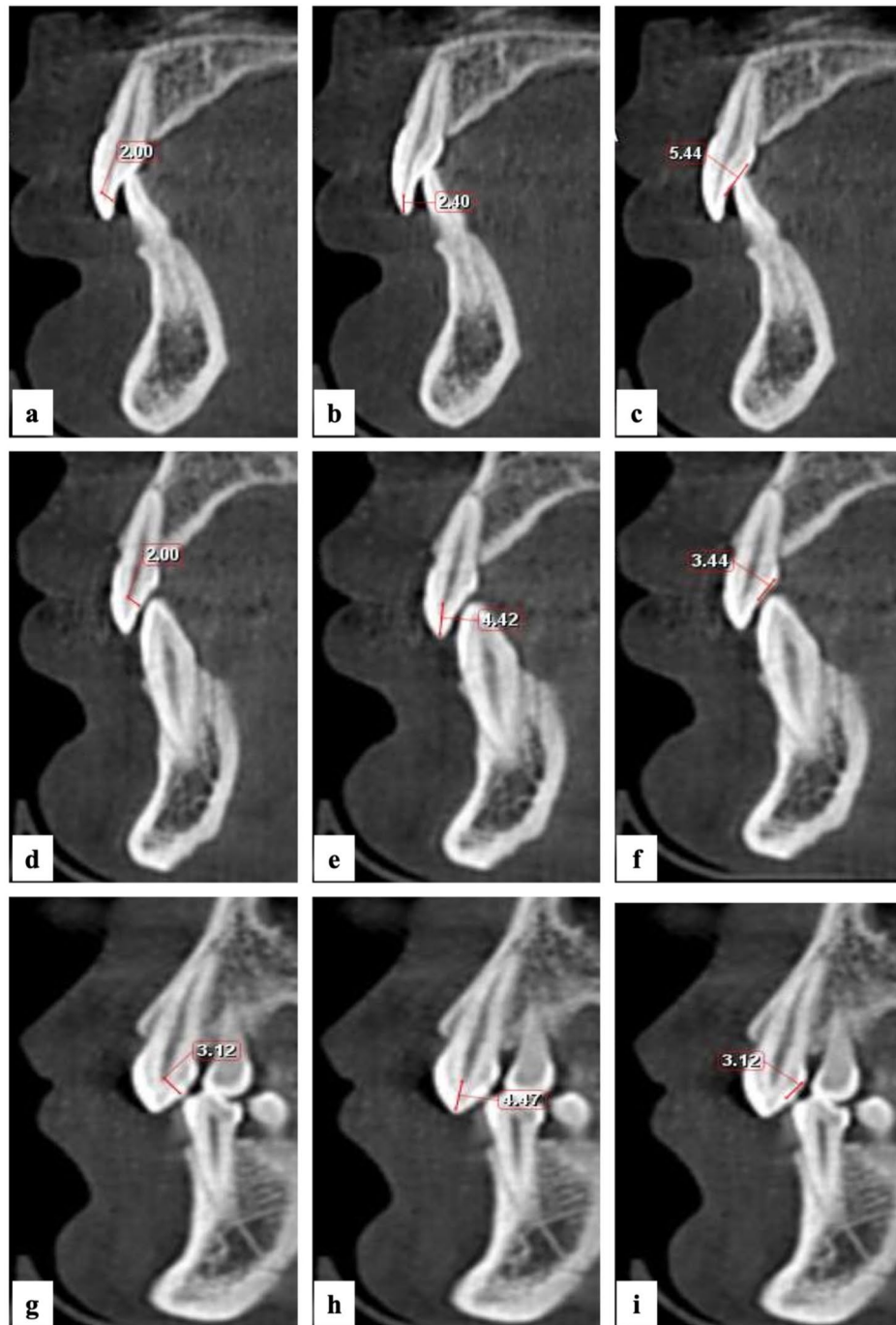


Fig. 2. Representative sagittal CBCT images, illustrating three principal odontometric variables for maxillary anterior teeth. (a – c) measured in maxillary central incisors, (d – f) in lateral incisors, and (g – i) in canines. (a, d, g): Distance from central fossa to the roof of the pulp chamber (CF–PC); (b, e, h): Distance from incisal edge to the roof of the pulp chamber (IE–PC); and (c, f, i): Distance from central fossa to the cingulum (CF–C).

- Lateral incisors differed significantly from central incisors in all three parameters, highlighting their clinical complexity.

The odontometric measurements were clearly different for anterior tooth types. Figure 3A shows how canines had the largest mean values for all 3 measurements (CF–PC, IE–PC, and CF–C) compared to the incisor types (lateral incisor & central incisor), trillions had the range of values of the incisor types, gender based comparisons (Fig. 3B) display that males were on average larger for most parameters with the most differences found in canines for CF–PC and IE–PC. The lateral incisor's greater variability between genders indicated that odontometric dimensions should always be considered as anatomical dimensions, based on biological sex and tooth siting.

Tooth	CF-PC (Mean ± SD)	IE-PC (Mean ± SD)	CF-C (Mean ± SD)
Central Incisor	2.21 ± 0.368	5.02 ± 0.774	4.41 ± 0.675
Lateral Incisor	2.86 ± 0.597	4.52 ± 1.399	3.41 ± 0.807
Canine	3.42 ± 0.848	4.90 ± 1.107	2.62 ± 0.793

Table 1. Descriptive statistics of odontometric parameters by tooth Type. CF-PC: Central Fossa to Pulp Chamber Roof; IE-PC: Incisal Edge to Pulp Chamber Roof; CF-C: Central Fossa to Cingulum.

Tooth	CF-PC (M vs. F)	CF-PC (p)	IE-PC (M vs. F)	IE-PC (p)	CF-C (M vs. F)	CF-C (p)
Central Incisor	2.31 vs. 2.05	< 0.001*	5.22 vs. 4.73	< 0.001*	4.45 vs. 4.38	0.304
Lateral Incisor	2.94 vs. 2.74	0.022*	4.52 vs. 4.52	0.996	3.45 vs. 3.37	0.690
Canine	3.49 vs. 3.32	0.172	5.00 vs. 4.80	0.281	2.67 vs. 2.57	0.287

Table 2. Gender-Based comparison of odontometric parameters (Male vs. Female, in mm). Values represent mean distances in millimeters (mm) for each odontometric parameter. CF-PC: Central Fossa to Pulp Chamber Roof; IE-PC: Incisal Edge to Pulp Chamber Roof; CF-C: Central Fossa to Cingulum. M: Male; F: Female. * indicates a statistically significant difference after independent samples t-tests.

Parameter	F-statistic	p-value	Post-hoc Summary
CF-PC	15.47	< 0.001	Canine > Lateral > Central
IE-PC	8.92	< 0.001	Central > Canine ≈ Lateral
CF-C	22.63	< 0.001	Central > Lateral > Canine

Table 3. Inter-Tooth comparison of odontometric parameters (ANOVA Summary).

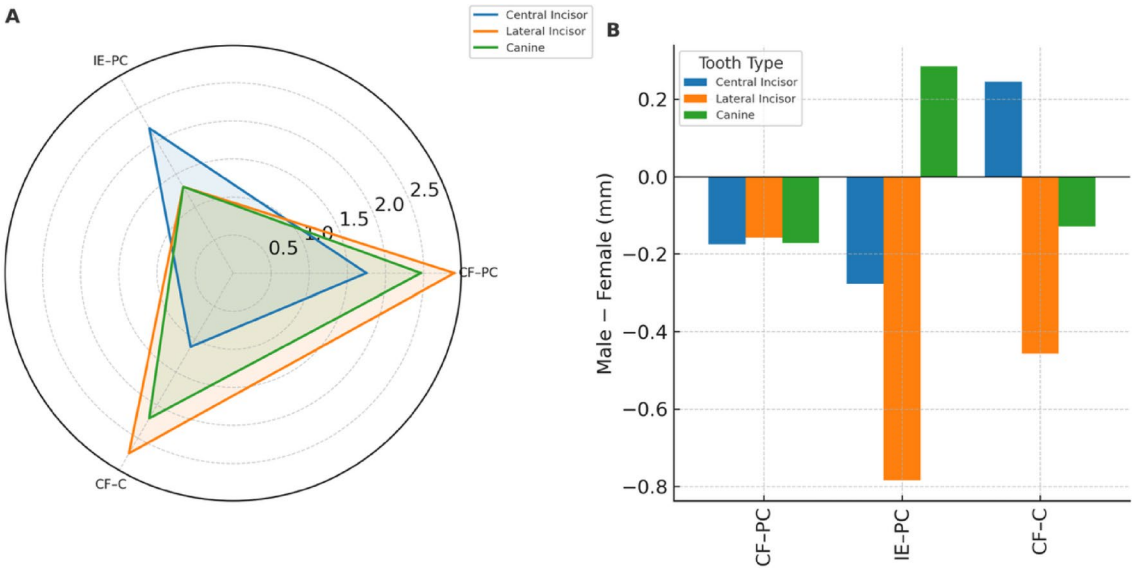


Fig. 3. Multi-parametric distribution of odontometric measurements across anterior teeth. (A) Radar plot showing comparative variation in cemento–floor to pulp chamber (CF-PC), inter-entrance to pulp chamber (IE-PC), and cemento–floor to canal orifice (CF-C) across central incisors (1), lateral incisors (2), and canines (3). Canines demonstrated consistently higher values across all parameters; (B) Bar chart depicting sex-based differences (male – female) for the same measurements by tooth type. Positive bars indicate larger dimensions in males, whereas negative values denote greater dimensions in females. Lateral incisors displayed the greatest variability, while canines showed the steepest CF-PC sex-related differences.

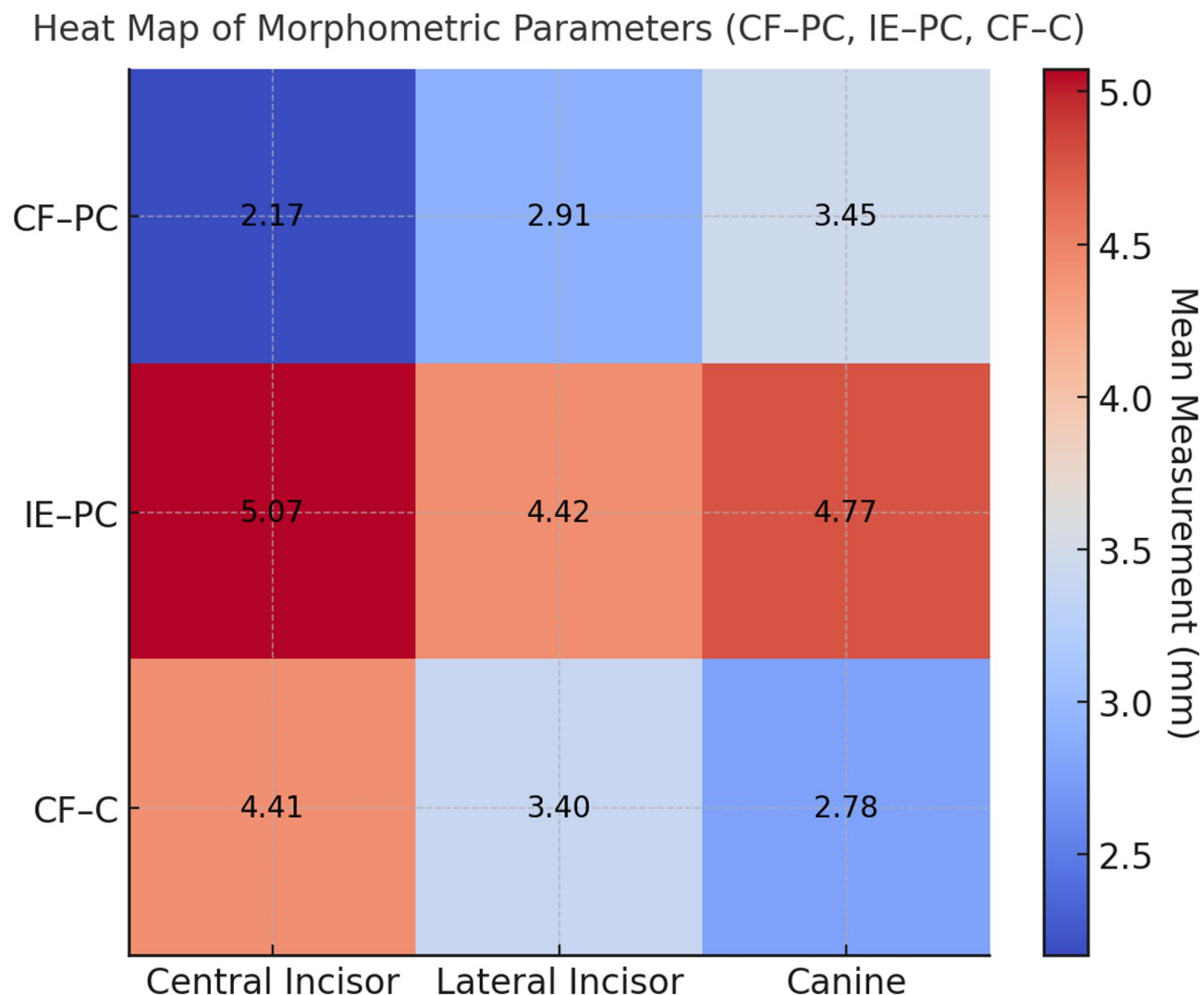


Fig. 4. Heat maps depicting distribution of CF-PC, IE-PC, and CF-C values across all samples. Blue = lower values, Red = higher values. Lateral incisors displayed the most heterogeneous distribution compared to central incisors and canines.

In an effort to improve visualization of morphometric variation, heat maps of CF-PC, IE-PC, and CF-C measurements across each individual sample have been constructed (Fig. 4). The color gradients (blue = low values, red = high values) illustrate the distribution patterns for each parameter, and mark the areas of increased anatomical complexity. Lateral incisors presented with the greatest range and most uneven distribution, while central incisors' measurements were all tightly clustered. The heat-map visual is a helpful supplement to the tabular data, allowing clinicians to very quickly identify teeth likely to be at greater procedural risk based on depth of penetration and angle of trajectory.

Discussion

This three-dimensional CBCT-based odontometric study of maxillary anterior teeth in an Indian population reveals important sex-based morphometric differences, which have important ramifications regarding the design of access cavities, procedural success, and injury prevention. Implementing population specific anatomical data into practice represents a shift to a promising future in precision, clinically relevant endodontics and addresses significant shortcomings of standardized treatment protocols that do not sufficiently recognize regional anatomical variations.

The observations of the sexual dimorphism in CF-PC and IE-PC can be matched with the existing knowledge of male and female differences in dental morphology. Males had significantly deeper pulp chambers, with the CF-PC distances of 2.31 mm compared with 2.05 mm for the central incisors ($p < 0.001$) and 2.94 mm compared with 2.74 mm for the lateral incisors ($p = 0.022$). This stands to support the volumetric CBCT studies that report males have more pulp volume (on average 12–15%), larger canal dimensions, and a larger crown-root proportion that is a result of greater dentoalveolar developments during adolescence²⁵. These morphological differences lay the basis for comprehending how anatomical variability can have direct clinical consequences.

Beyond morphological interest, this phenomenon is clinically significant since it directly affects treatment outcomes. Studies have found that the rate of undetected canals in teeth that have undergone endodontic treatment ranges from 13.3% to 42%, with lateral incisors showing the highest failure rates at 33.3%^{26,27}. The significant morphometric variability in lateral incisors (IE-PC SD = 1.399 mm) observed among our study participants is linked to these higher complication rates, indicating that anatomical complexity directly affects procedural success. Additionally, research based on population outcomes shows that endodontic failure rates can differ greatly among various demographic groups, with some populations experiencing up to a 32% increase in failure rates when standardized protocols, originally developed for other populations, are used²⁸. This emphasizes the significance of adapting procedures to the patient population's unique morphometric traits rather than relying exclusively on generic protocols.

The diverse epidemiologic studies done on more than 1.4 million teeth show teeth that received endodontic treatment have an eight-year retention rate that is 97%^{29,30}. Yet, these (usually) high retention rates assume appropriate case selection and possibly altered techniques to acknowledge different anatomy of teeth. The current evaluation revealed a sex difference, which leads one to suggest that neglecting demographic differences could ultimately replicate or worse outcomes, particularly in certain populations. Another contributing factor to failure in treatment is iatrogenic injury, which may be prevented or at least reduced through adequate knowledge of anatomy.

Iatrogenic perforations are a significant complication of endodontic procedures and worldwide studies have shown incidence occur between 0.6% and 17.6%³¹. Data indicate that treatment failures due to perforations can occur 20–30% of the time and, of these, only around 30% will demonstrate successful healing³². In the studied samples, the males also had lower CF-PC values meaning deeper pulp chamber sizes, there will need to be more specificity in depth controls and angulation strategies to reduce the risk of iatrogenic injury. Given that the perforation rates of maxillary teeth are 41%, and that anatomical complexity is a major contributing factor, the risk categorization that was developed from our morphometric data is especially relevant³³. Although our study concentrates on maxillary anterior teeth, the principle that anatomical variation influences complication rates is consistently applicable across different tooth types³⁴. Technological innovations in guided endodontics offer promising solutions to these challenges.

Guided endodontic protocols using 3D-printed templates has proven to significantly reduce procedural errors with a success rate of 98.3% as opposed to 81% with conventional freehand access methods²². This provides a new approach to mitigating the potential for perforation while increasing access trajectory accuracy using morphometric data that is population-specific. Building on this, our morphometric parameters can inform the development of structured access cavity design strategies tailored to population needs.

The morphometric parameters described in this analysis offer a measure of guidance to develop access algorithms for different populations. Access trajectories must provide a way for both individuals and populations via effective dimensions related to gender and tooth type specificity, which is exemplified by the significance of CF-C values for tooth types (Central > Lateral > Canine, $F = 22.63$, $p < 0.001$). It is noteworthy that males were greater in IE-PC and CF-PC, and thus a systematic reorientation of incisal access angles may be merited as a measure to make sure biomechanical advantages remain intact, and procedural access concerns do not present issues.

Recent empirical evidence strongly supports moving away from traditional “straight-line” access, towards minimally invasive access cavity designs (MIAC)³⁵. Literature shows that traditional access preparations can remove approx. Approximately 40% of peri-cervical dentin thickness, while access via the incisal, when using a MIAC approach better preserves important tooth structure and fracture resistance³⁶. These evidence based transitions are supported by our morphometric data which serves as tabulated, quantifiable guides for prudently planning access while conserving tooth structure and providing sufficient access to canals. The data supports an organized clinical decision aid based on anatomic data.

The values presented here can be understood primarily as baseline morphometrics, instead of normative base-line morphometric data. The value of these measurements lies primarily in their ability to provide clinicians with evidence-based base lines (ground zero) for planning access - either particularly in cases where external landmarks were ambiguous (e.g., heavily restored teeth, calcified canals). For example, given the steeper CF-PC trajectory of canines, the initial bur angulation would need to be more palatally inclined with depth control depending on the CF-C values to avoid over-preparation. Similarly, in the more morphometrically variable lateral incisors we produced a two-phase access: conservative first entry in phase one followed by full CBCT-guided access, only if appropriately difficult to negotiate the canal in phase two. These examples show how our data can translate to pragmatic changes to how the access is prepared rather than saying you must always use these values as cut-offs.

The formulation of decision trees containing morphometric variables, patient variables, and tooth variables clearly represents a reasonable progression toward computer based endodontic treatment planning protocols. It would yield evidence-based advice for how to angle the bur, how deep to penetrate, and what size to extend the access cavity to, and would be particularly beneficial for inexperienced practitioners when anatomical landmarks are travestied by trauma, attrition, or extensive restoration. However, effective use of these data also requires understanding variability across different tooth types.

The notable morphometric variability means that adaptive treatment approaches are needed due to anatomical complexity. Central incisors showed fairly predictable behavior (IE-PC SD = 0.774 mm) meaning they could have the most efficient use of standardized protocol approaches. Meanwhile, lateral incisors require a progressive, step-wise assessment strategy and continual reassessment due to considerable variability (IE-PC SD = 1.399 mm). This finding is supported by a study which indicated that lateral incisors showed the highest missed canal (33.3%) rates among anterior teeth²⁶.

Although the lateral incisors within our cohort demonstrated the highest standard deviation for all parameters, we recognize that variability does not always equate to increased clinical difficulty. We would, instead, propose a multilevel model in that teeth with a greater morphometric variability like lateral incisors would be managed with preoperative CBCT imaging and dynamic guidance, while predictable dimensions of central incisors demonstrate acceptable risk for everyday practice. Variability should be taken into account along with other components of the clinical picture including restoration history, occlusal components, and patient risk not as an individual feature for access design.

Meta-analytical information from retreatment studies indicates that the incidence of instrument separation failures increases to 21% when fragments are in the apical third compared to 8.8% in the middle or coronal third³³. The morphometric differences observed in this study indicate that protocols may be area-specific, which may help avoid some complications by modifying initial access preparation and being able to prepare based on predictable anatomical pathways. Recent studies scrutinizing the accuracy of guided endodontics have shown linear deviations from 0.13 ± 0.21 mm coronally to 0.46 ± 0.4 mm apically, and angular deviations at $2.8 \pm 2.6^\circ$ ²². Factors relating our morphometric data to these precision parameters may allow the endodontist to design templates with greater clinical accuracy for the Indian populations, which could improve canal accessibility while decreasing risk of complications. These clinical applications also have far-reaching implications for education and policy.

The morphometric variability noted in this Indian population should lead to a complete reconstruction of the protocols used in endodontic training. The current curricula have limited use of western anatomical references while teaching procedures and would not have considered geographical variations, which may lead to suboptimal treatment outcomes^{37,38}. The incorporation of clinically relevant norms of morphometrics as they relate to specific populations in the curriculum will be a major step toward cultural competence, and, better yet, culturally appropriate dental care.

Studies conducted worldwide on endodontic educational outcomes have demonstrated that adopting systematic, protocolized, and standardized approaches, the use of advanced visualization tools, can significantly improve technical outcomes and decrease the proportion of missed canals^{39,40}. In fact, many of the aforementioned protocolized educational models seem to create opportunities to include morphometric data associated with specific populations that may enhance training by allowing practitioners to appreciate local anatomical variation and the implications of that variation in relation to clinical practice⁴¹. Beyond training, the integration of this knowledge into technological workflows offers a path toward transformative clinical practice.

Studies looking at undergraduate outcomes for endodontics, illustrate that there are generally higher levels of procedural success for vital pulps (87–8%) versus necrotic pulps (65.6%), but that variability existed based on operator experience and the nature of their training program³⁹. Including anatomical knowledge related to specific populations within training programming could easily minimize the level of variability observed in clinical outcomes⁴², subsequently contributing to overall improvements in clinical performance across the continuum of experience in endodontics.

The morphometric parameters identified in this study provide excellent input data for new guide-based endodontic workflows. Static guided endodontic methods with 3D-printed templates have remarkable accuracy; studies report report angular deviations as low as 1.71° as an intrinsic error for optimized sleeve designs^{22,23}. The combination of population-specific morphometric norms and guides could be a step forward, in terms of beacon and precision, in delivering a treatment plan.

Low-cost 3D printing technology now allows for a guided endodontic method to be realised for the masses. Desktop 3D printers can reach accurate tolerances in the clinical realm when creating templates for modifying a template for a guided procedure for an RCT⁴³. The combination of the morphometric measurements from this study with low-cost guided endodontic technology could enable equitable access to precision endodontic treatment in underserved locales.

Dynamic guided endodontic strategies with real-time navigation methods are more accurate and efficient than conventional means, with a further advantage in negotiations with calcified canals⁴⁴. In the future, real-time navigation may incorporate population-based morphometric databases to provide real-time directional apologies to treatment plans for complex clinical presentations.

The findings of this study were derived from only one institution in one geographic area of India, despite an adequate power analysis of 600 teeth. As such, the sample may not reflect the regional variations, or dietary or functional aspects of the greater Indian population. Additionally, occlusal wear, old restorations, and parafunctional habits were not controlled for because they were beyond the scope of retrospective radiographic analysis. Future multi-center studies with stratified sampling and these as confounders are needed to validate and generalize these findings to a national level.

Despite the limitations, we provide the first complete morphometric analysis of maxillary anterior teeth using CBCT in an Indian population, and developed important baseline information for population-specific endodontic protocols. The very different CF-PC and IE-PC measurements we documented as well as the statistically significant differences based on sex, namely the pattern that males had consistently greater measurements (CF-PC and IE-PC), provide immediate opportunities for clinical improvement by evolving access cavity design to better accommodate the maximum canal opening and potentially reduce treatment complications.

The immediate clinical implications are developing population-specific access templates, and reframing treatment protocols that are currently in use. Ultimately, additional clinical- or practice-based validation studies comparing treatment outcomes of Indian morphometric protocols to standardized ones would provide the strongest evidence of a clinical benefit and cost-effectiveness.

The combination of artificial intelligence and machine learning technologies with population-specific morphometric databases has major implications for the practice of endodontics. AI-driven treatment planning

systems could potentially offer real-time evidence-based recommendations on the design of access cavity preparation, selection of instruments, and modification of weeks or months-old procedures based on anatomical parameters specific to the patient.

Future studies should explore how value-based health care will be more clearly defined by population-specific endodontic protocols, including cost-benefit analysis of guided endodontics and long-term survival of treatment steps, as evidence informs health policies and strategic resource allocation in the provision of dental care to diverse populations.

Conclusion

This study used CBCT to provide initial morphometric measurements of the maxillary anterior teeth of a young Indian population and found significant intra-group differences by tooth type, also by gender with males having deeper pulp chambers and found that lateral incisors supposedly had a greater range of values. These conclusions add to the clarity of the anatomical characteristics of this population; however, they cannot be called definitive or base-line morphometric data, they are starting points from a single institution study that has limitations associated with being localized and also confounded by occlusal wear and unreported restorations. Additionally, the data has indirect implications; mean values with narrow confidence intervals for central incisors and wide confidence intervals for lateral incisors demonstrate some degree of predictability and a range of variability for this population.

In clinical practice, these measurements might serve as a useful tool to inform risk-based access planning where it would recommend conservative initial access in the case of predictable teeth like the central incisor while recommending preoperative CBCT or guided endodontics for teeth with anatomical variations like the lateral incisor. While useful for immediate clinical application, those data can be shared for a better understanding of the profession's direction and be leveraged for decision-support tools, educational modules in dental education as well as organizations developing AI or software-assisted treatment planning programs. To effectively confirm these findings and ultimately transform these findings into standard clinical guidelines, further multi-centre studies that include broader demographics and link morphometric data to treatment outcomes are required.

Data availability

Data is provided within the supplementary information files.

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Author contributions

MAK and AMP conceived and designed the study. MAK and AMP collected the data and performed the primary data analysis. AB provided statistical expertise and contributed to the data interpretation. DAW and DD assisted with the literature review and contextualization of the findings. AMP contributed to the study design and data validation. TPDP, AM, and SA provided guidance on the methodology. MAK and AMP drafted the manuscript and DAW and DD provided critical revisions. All authors reviewed and approved the final manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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