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Age-dependent patterns of root canal curvature in mandibular first molars

Özge Başar,[1] Burcu Pirimoğlu,[2] Ali Keleş,[3] Cangül Keskin[4]

[1]*Turkuaz Dental Clinic, Izmir, Türkiye*
[2]*Ondokuz Mayıs University, Graduate School of Educational Sciences, Samsun, Türkiye*
[3]*Department of Endodontics, Bolu Abant İzzet Baysal University Faculty of Dentistry, Bolu, Türkiye*
[4]*Department of Endodontics, Ondokuz Mayıs University Faculty of Dentistry, Samsun, Türkiye*

Purpose: This laboratory study aimed to evaluate age-related differences in root canal curvature of human mandibular first molars using high-resolution micro-computed tomography (micro-CT).

Methods: Mesial roots of extracted human mandibular first molars (n=93) were collected and classified into three age groups: ≤30 Years, 31–59 years, and ≥60 years. The root canal curvature was evaluated in both the mesiodistal and buccolingual planes using micro-CT reconstructions analyzed in AutoCAD according to Pruett's method.

Results: Curvature values were consistently greater in the buccolingual than in the mesiodistal plane across all age groups. Mesiobuccal and mesiolingual canals exhibited similar patterns, and no significant differences were observed among the age groups ($p>0.05$).

Conclusion: Mandibular first molars exhibited consistent canal curvature across age groups. Although age did not significantly affect this parameter, careful preparation and appropriate instrument selection remain essential for mesial canals in all patients.

Keywords: Aging; curvature; mandibular molar; micro-CT; root canal.

Introduction

The complexity of root canal morphology is one of the major determinants in endodontic treatment success. This includes the canal configuration, accessory canals, and isthmuses, as well as apical deltas (1). Among these, root canal curvature is particularly critical because it directly influences the mechanics of shaping, the effectiveness of irrigation, and the quality of obturation (2–5), thereby playing a decisive role in the long-term success of endodontic therapy. Excessive curvature increases the risk of procedural errors such as ledging, transportation, instrument separation, and perforation, which may compromise long-term prognosis. Thus, a precise understanding of root canal curvature is essential for both clinical decision-making and the development of safer instrumentation techniques (6).

Age is an important factor influencing root canal morphology and, consequently, treatment complexity. Secondary dentin deposition, calcification, and canal sclerosis occur progressively with aging, leading to narrowing of the

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Correspondence: Ozge Basar. Turkuaz Dental Clinic, Izmir, Türkiye
Tel: +90 505 – 413 11 40 e-mail: basar.ozge@hotmail.com
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canal lumen and alterations in root canal anatomy (7,8). Although several studies (9–11) have examined the effect of aging on canal diameter, pulp chamber volume, and dentin thickness, the influence of aging on canal curvature has not been fully clarified. This gap is especially relevant in mandibular molars, given their anatomical complexity, including multiple roots and the frequent curvature of mesial canals, all of which increase the difficulty of endodontic procedures (12).

Over the years, several methods have been proposed to measure root canal curvature. (13–16) The most widely used approach was introduced by Schneider (16), which measures the angle of curvature in two-dimensional radiographs. The Schneider technique yields a 2D angle on radiographs, which is simple yet insensitive to the tightness of the bend and to out-of-plane curvature. The Pruett method (5) characterizes curvature by both the angle and the radius of the best-fit circular arc to the curved segment. Reporting angle and radius offers a more clinically meaningful descriptor of curvature severity than angle alone. As a result, curvature assessment frameworks that incorporate both angular deviation and the radius of curvature offer a more comprehensive understanding of root canal geometry (17–19). In addition, compared with conventional radiography and cone beam computed tomography (CBCT), micro-computed tomography (micro-CT) enables precise evaluation of curvature in multiple planes and offers reliable quantitative measurements of canal geometry (2).

To date, only limited evidence has examined whether age affects canal curvature and whether this influence varies among different root canals. Clarifying this relationship is important for anticipating clinical challenges in elderly patients and refining strategies for root canal preparation. Accordingly, this study tested the null hypothesis that age does not have a significant effect on root canal curvature.

Materials and Methods

The manuscript of this laboratory study was written according to the Preferred Reporting Items for Laboratory Studies in Endodontology (PRILE) 2021 guideline (20). The study protocol was approved by the local ethics committee (OMU KAEK-2024/46). It involved extracted human teeth and was conducted in accordance with the Declaration of Helsinki. The required sample size was calculated as 18 specimens per group (effect size: 2.70). To allow balanced allocation across the three age groups and to further increase statistical robustness, the final sample size was set to 31 teeth per group (total n=93).

A total of 93 human mandibular first molars with complete root formation, free of caries, resorption, or prior endodontic treatment, were collected from patients with known ages after informed consent, in accordance with the Declaration of Helsinki. Micro-CT imaging was performed with the Skyscan 1172 unit (Bruker, Kontich, Belgium) at 13.68 µm resolution, operating at 100 kV and 100 µA, with 180° rotation steps of 0.6°. An Al–Cu alloy filter was used, and images were reconstructed with NRecon (v.1.7.1.1; Bruker-microCT) applying standardized parameters for smoothing (3), contrast adjustment (0.011–0.019), and 15% beam hardening correction. The selected specimens were divided into three age-based groups: ≤30 Years, 31–59 years, and ≥60 years. Three-dimensional models were obtained using CTAn (version 1.18.8.0+, Bruker-microCT) and visualized in CTVol (v.2.3.1.0, Bruker-microCT). The alignment of mesiodistal (MD) and buccolingual (BL) directions was ensured by DataViewer (v.1.5.6 Bruker micro-CT).

Root canal curvature was evaluated in both the MD and BL planes using three-dimensional reconstructed micro-CT images using AutoCAD (Autodesk, San Rafael, USA). Curvature was characterized according to the method described by Pruett et al. (5) which defines the canal curvature as a segment of a circular arc. Two parameters were recorded for each canal:

(1) The angle of curvature (θ, in degrees), defined as the angle subtended between the straight-line segments extending from the canal orifice to the point of maximum deflection, and from that point to the apical terminus;

(2) the radius of curvature (r, in millimeters), calculated as the radius of the circular arc that best fits the curved portion of the canal.

All analyses were performed by an experienced researcher on micro-CT images who was blinded to the patients' ages (B. P.).

All statistical analyses were performed using SPSS (v.21 IBM, Chicago, IL, USA) with a 5% significance threshold. Normality was assessed with the Shapiro–Wilk test ($p>0.05$), and homogeneity of variances was confirmed with Levene's test ($p>0.05$). Based on these assumptions, one-way ANOVA was used for group comparisons.

Results

The mean radius and angle of curvature for the mesiobuccal (MB) and mesiolingual (ML) canals, measured in both BL and MD directions, are summarized in Table 1. Across all groups, curvature in the BL direction was consistently more pronounced than in the MD direction, as reflected by higher mean curvature angles. No statistically significant differences were observed in either curvature angle or radius among the three age groups (≤30 years, 31–59

Table 1. Descriptive statistics (mean± standard deviation) for curvature values (mm) and angle (°)

Root Canal	Direction	Age	Radius of curvature (mm)	Angle of curvature (°)
MB Canal	BL direction	≤30 years	12.1±0.99	36.0±9.98
		31–59 years	11.3±0.70	37.1±10.6
		≥60 years	13.4±0.82	31.5±8.40
	MD direction	≤30 years	11.8±0.42	20.1±13.4
		31–59 years	9.56±1.13	19.6±8.18
		≥60 years	10.0±1.94	18.2±8.71
ML Canal	BL direction	≤30 years	11.5±0.65	37.6±8.40
		31–59 years	10.9±0.74	37.6±10.7
		≥60 years	12.5±0.93	39.0±12.7
	MD direction	≤30 years	11.7±1.56	19.1±10.9
		31–59 years	9.56±0.37	19.6±8.40
		≥60 years	10.0±0.34	15.1±12.7

MB: Mesiobuccal; ML: Mesiolingual; BL: Buccolingual; MD: Mesiodistal.

years, and ≥60 years) for both the MB and ML canals in either BL or MD direction ($p>0.05$).

Discussion

Root canal curvature is an important factor influencing shaping, irrigation, and the risk of procedural errors (6). Since aging alters dentin and canal morphology, its possible effect on curvature has been questioned. The results of this study indicated that root canal curvature was consistent across age groups in mandibular first molars. Although mesial canal curvatures showed a tendency to increase with advancing age, this trend did not reach statistical significance. The findings suggest that while age may influence factors such as dentin thickness and apical diameter —as previously demonstrated in several studies (21,22) — its effect on root canal curvature does not appear to be significant based on the available evidence and requires further investigation. Consistent with our results, Keskin et al. (23) demonstrated, through micro-CT evaluation of mandibular first molars, that mesial canal curvature was not associated with age. It was shown that while root canal volume and surface area decreased with age, the overall root canal configuration did not exhibit substantial alterations. This apparent stability of curvature despite age-related reductions in canal volume and surface area may be explained by several factors. First, secondary dentin apposition and calcification typically occur concentrically, producing a uniform narrowing of the lumen rather than directional changes in the canal pathway (24). Second, the overall curvature of the root canal is largely established during tooth development and remains stable once root formation is complete, indicating that age-related changes predominantly influence canal dimensions rather than trajectory (25). Third, dentin sclerosis and apical narrowing alter the internal diameter and working length but are unlikely to modify the long-axis orientation of the canal. Finally, while volumetric and surface area changes reflect micro-morphological alterations, curvature is a macro-anatomical parameter that tends to remain constant unless disrupted by pathologic or iatrogenic processes (26). Taken together, these considerations help to explain why curvature did not vary significantly with age, even though other morphometric parameters did.

Mesial canals consistently demonstrated higher curvature than distal canals, corroborating previous anatomical studies reported in the literature (6,27), which made them a suitable focus for detailed evaluation in this study. Even though no significant age-related differences were detected, the consistently higher curvature of mesial canals confirms that they demand greater clinical attention in all patients. The presence of frequent isthmuses, narrower diameters, and sharper curvatures in mesial canals further increases the difficulty of negotiation and shaping (28). Clinically, these features highlight the importance of establishing a secure glide path, using pre-curved hand files, and selecting instruments with enhanced flexibility regardless of age (29). Moreover, conservative taper preparations and minimally invasive shaping approaches are particularly advisable in mesial canals to reduce the risk of iatrogenic errors (30). These findings reinforce the view that mesial canals inherently present greater challenges than distal canals, and careful technique remains essential across all age groups. Although canal curvature did not differ significantly among age groups, the clinical relevance of evaluating this parameter in the context of aging remains important. Age-related dentin sclerosis, and decreased pulp space volume increase the difficulty of canal negotiation and cleaning, particularly in curved canals (21).

Clinically, the predominance of buccolingual curvature highlights an important limitation of conventional periapical radiographs, which visualize the canal anatomy primarily in the mesiodistal plane and therefore tend to underestimate the true three-dimensional extent of curvature (31). This limitation can lead to inaccurate assessment of canal complexity and potential misjudgment of instrumentation risk, particularly in mesial roots where double-plane curvatures are common (15). In contrast, three-dimensional imaging modalities such as micro-CT and CBCT enable visualization of the canal trajectory in both BL and MD directions, offering a more comprehensive understanding of root canal anatomy (32).

A notable strength of this study is the use of high-resolution micro-CT for accurate visualizations. Although curvature measurements were performed on two-dimensional projections of the reconstructed images using AutoCAD, this approach allowed accurate and reproducible determination of curvature parameters in both MD and BL planes. The high scanning resolution of micro-CT minimized observer bias and ensured consistent identification of the curvature path (32,33). While true three-dimensional curvature modeling was not applied, the bidirectional evaluation of curvature provided a reliable approximation of canal geometry and allowed meaningful comparisons among age groups.

The sample was limited to mandibular first molars with complete root formation, which restricts the generalizability of the findings to other tooth types and developmental stages, a limitation of the study. In addition, although micro-CT provides highly accurate three-dimensional reconstructions, it remains an in vitro technique that cannot fully reproduce clinical conditions and patient-related biological variability. The cross-sectional design also prevents the assessment of longitudinal changes in the same teeth over time, which may underestimate the dynamic nature of age-related alterations (33). Future investigations should broaden the scope by including multi-center datasets and diverse ethnic cohorts to better capture geographic variability and population-level patterns. Analyzing age as a continuous variable may reveal subtle associations with canal curvature, while adding indices such as calcification, dentin hardness, root length, and isthmus presence would provide a more complete view of age-related changes (9). Incorporating longitudinal imaging of extracted teeth or serial in vivo CBCT datasets from patients could further clarify temporal dynamics, although the use of CBCT solely for research purposes is not recommended in endodontics (34). In addition to age, other biological and environmental factors, including gender, systemic conditions, and restorative status may also influence root canal morphology. Considering these variables in future studies could yield a more complete picture. Finally, anatomical features are recommended to be associated with clinically relevant endpoints, including shaping errors, instrument separation, irrigation efficacy, and postoperative pain. Such studies would bridge laboratory observations with patient-centered outcomes, ultimately refining treatment protocols across different age groups.

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Informed consent: Written informed consent was obtained from patients who participated in this study.

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