BMC Oral Health

RESEARCH

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Influence of CBCT device, voxel size, and segmentation software on the accuracy of tooth volume measurements

Melih Ozdede[1*], Gulsun Akay[2] and Ozge Karadag Atas[3]

Abstract

Objective This study aimed to assess the influence of cone-beam computed tomography (CBCT) device type, voxel resolution, and segmentation software on the accuracy of tooth volume measurements.

Materials and methods Thirty extracted single-rooted human incisor teeth were included. Physical volumes were determined using the Archimedes water displacement method (WDM) as the gold standard. Each tooth was scanned using two CBCT devices (Planmeca Promax 3D-Mid and NewTom 5G-XL) at two voxel sizes (0.1-mm and 0.2-mm). Segmentation was performed using two semi-automatic software programs: 3D Slicer and ITK-SNAP. Volumetric deviations from WDM were statistically analyzed using repeated-measures ANOVA, with the significance level set at $p < 0.05$.

Results Although the differences between the two CBCT devices ($p = 0.431$) and voxel sizes ($p = 0.070$) were not statistically significant, a trend toward improved volumetric accuracy was noted with the Planmeca Promax 3D-Mid device and the 0.1 mm voxel size. In contrast, a statistically significant difference was found between the segmentation programs ($p < 0.001$). ITK-SNAP consistently produced higher volume deviations compared to both 3D Slicer and the gold-standard WDM. The most accurate results were achieved using the Planmeca Promax 3D-Mid device, a 0.1 mm voxel size, and the 3D Slicer software, with no statistically significant deviation from WDM ($p = 0.467$).

Conclusion CBCT device selection and voxel size (0.1-mm vs. 0.2-mm) did not significantly affect volumetric accuracy in single-rooted incisor teeth. However, the choice of segmentation software played a critical role, with 3D Slicer providing measurements closest to the gold standard. These findings highlight the importance of software selection in CBCT-based volumetric measurements for dental applications, though the results may be limited to teeth with similar anatomical complexity (e.g., single-rooted incisors).

Keywords Cone-beam computed tomography, Image reconstruction, Segmentation, Tooth, Digital imaging, Tooth volume, Voxel size

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Introduction

In recent years, cone-beam computed tomography (CBCT) has gained widespread use in dental diagnostics due to its capability to provide high-resolution, three-dimensional imaging of maxillofacial hard tissues. It is commonly used for the evaluation of pathological or morphological conditions, volumetric assessments, and treatment planning [1]. Volumetric measurements play a vital role in age estimation, personal identification, forensic odontology, and maxillofacial reconstruction [2]. Additionally, such measurements and the evaluation of tooth morphology are often necessary for planning and performing surgical, prosthetic, and endodontic procedures [3].

Previous studies have indicated that CBCT imaging parameters—particularly voxel size—significantly influence the accuracy of volumetric measurements [1, 4]. CBCT systems provide a range of voxel sizes, typically between 0.07 mm and 0.60 mm [5]. As voxel size decreases, image resolution improves; however, this generally results in higher radiation exposure [6, 7]. Consequently, selecting an optimal voxel size is essential to balance diagnostic accuracy with radiation safety.

The accuracy of volumetric analysis is also highly contingent upon the segmentation method and the software employed. Segmentation techniques include manual, semi-automatic, and automatic methods. Due to the time-consuming nature of manual segmentation and the potential limitations in certain fully automatic approaches—particularly in anatomically complex cases—semi-automatic segmentation has become the preferred method in many studies as it offers a balance between speed and user control [8, 9]. However, recent studies have also reported promising results using fully automatic segmentation methods, suggesting that their reliability is improving with advancements in deep learning techniques. Volumetric results may still vary depending on the software employed [4, 10, 11].

Accurate tooth volume measurement is crucial for several clinical applications, such as endodontic treatment planning, orthodontic assessment, and forensic investigations. Thus, identifying the optimal combination of imaging and segmentation parameters is essential for ensuring reliable volumetric assessments. In this context, voxel size, CBCT device, and segmentation software are key variables affecting volumetric accuracy. While previous studies have examined these factors independently, to the best of our knowledge, no study has simultaneously evaluated all three under a unified experimental protocol [1, 4, 6].

The null hypothesis posits that voxel size, CBCT device, and segmentation software do not significantly affect volumetric accuracy compared to the gold standard. Accordingly, this study aims to assess the effects of different CBCT devices, voxel sizes, and segmentation programs on the accuracy of tooth volume measurements.

Materials and methods

Study design and ethical approval

This ex vivo experimental study was conducted in accordance with the Declaration of Helsinki. Ethical approval was obtained from the Non-Interventional Clinical Research Ethics Committee of our university (Date: 15.04.2021, No: E-60116787-020-44426) prior to the initiation of the study.

A priori power analysis determined that a minimum of 30 samples was required to achieve 95% power at an effect size of $w = 0.35$. Accordingly, 30 human single-rooted incisor teeth, extracted for various clinical reasons, were included in the study. All teeth were collected from the oral surgery department of our university following extraction procedures performed as part of routine dental treatment. Donor patients provided informed consent for the use of their extracted teeth in scientific research.

Specimen selection and Preparation

Teeth exhibiting fractures, restorations, resorption, cracks, or other morphological anomalies were excluded. All specimens were thoroughly cleaned under running water and mounted individually on wax blocks for imaging.

Gold standard volume measurement

The physical volumes of the teeth were measured using the WDM, which served as the gold standard. Each specimen was immersed in a graduated cylinder, and the displaced water volume was recorded in millimeters cubed (mm^3).

CBCT imaging protocols

Each tooth was scanned using two different CBCT devices at two voxel resolutions (0.1-mm and 0.2-mm), employing the narrowest available field of view (FOV) in each system.

- Planmeca Promax 3D-Mid (Planmeca Oy, Helsinki, Finland):

90 kVp, 5–9 mA, 4.05 s exposure, 4.0 × 5.0 cm FOV.

- NewTom 5G-XL (Quantitative Radiology, Verona, Italy):

110 kVp, 11.4 mA, 9 s exposure, 6.0 × 6.0 cm FOV.

All samples were immobilized in wax blocks during image acquisition. CBCT data were exported in Digital Imaging and Communications in Medicine (DICOM) format for further analysis.

Segmentation software and volume analysis

Two semi-automatic segmentation programs were used for volumetric analysis: 3D Slicer (v5.6.2, BSD license, CA, USA) and ITK-SNAP (v3.8.0, Cognitica, Philadelphia, PA, USA).

- In 3D Slicer, the "Segment Editor" module was used to manually define the region of interest (ROI) in multiple slices, followed by semi-automatic refinement using predefined grayscale thresholds. Volume data were calculated using the "Segment Statistics" module (Fig. 1).
- In ITK-SNAP, segmentation was performed using active contour methods initiated with seed (bubble) points. Threshold ranges were adjusted based on grayscale and contrast optimization. The region-growing algorithm progressed semi-automatically to generate 3D segmentations, which were then used for volumetric calculations (Fig. 2).

For 3D Slicer, grayscale threshold values were manually adjusted after visual inspection to ensure accurate delineation of enamel, dentin, and pulp boundaries. The range typically fell between 500 and 2500 HU, though adjustments were permitted to account for inter-sample density variation. In ITK-SNAP, the "Automatic Thresholding" option using intensity histogram analysis was applied, and seed points were manually placed in central high-density regions to initiate segmentation. When inconsistencies arose between preliminary and final segmentations, consensus was reached through joint review by two dentomaxillofacial radiologists during the calibration session. To maintain consistency, the same grayscale range and segmentation criteria were applied across all samples whenever technically feasible.

Observer blinding and calibration

To eliminate potential bias, all observers were blinded to the WDM results during segmentation. A pre-assessment calibration session was conducted to standardize segmentation procedures among observers.

Observer reliability assessment

Intra-observer reliability was assessed by having the first observer re-analyze 20% of the samples after a two-week interval. Inter-observer reliability was evaluated by having the second observer independently analyze another 20% of the data. Intraclass correlation coefficients (ICC) were used to assess agreement levels.

While ICC values indicated high reliability, it is acknowledged that intra-observer variability could influence the boundary delineation, especially in cases with ambiguous grayscale transitions or partial volume effects. To minimize this, a detailed segmentation protocol was developed and followed consistently. The use of semi-automatic tools with fixed threshold criteria further helped reduce subjective variation across repeated measurements.

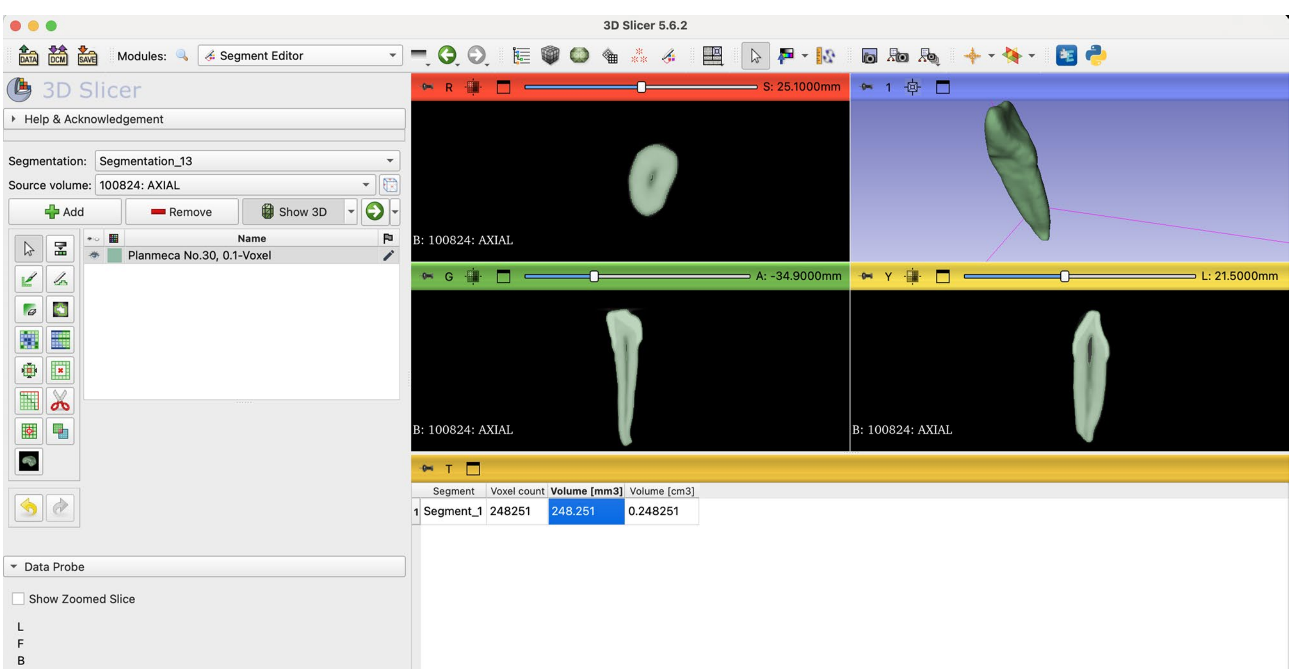

Fig. 1 Volumetric analysis with semi-automatic segmentation in the 3D-Slicer program, 0.1-mm voxel size

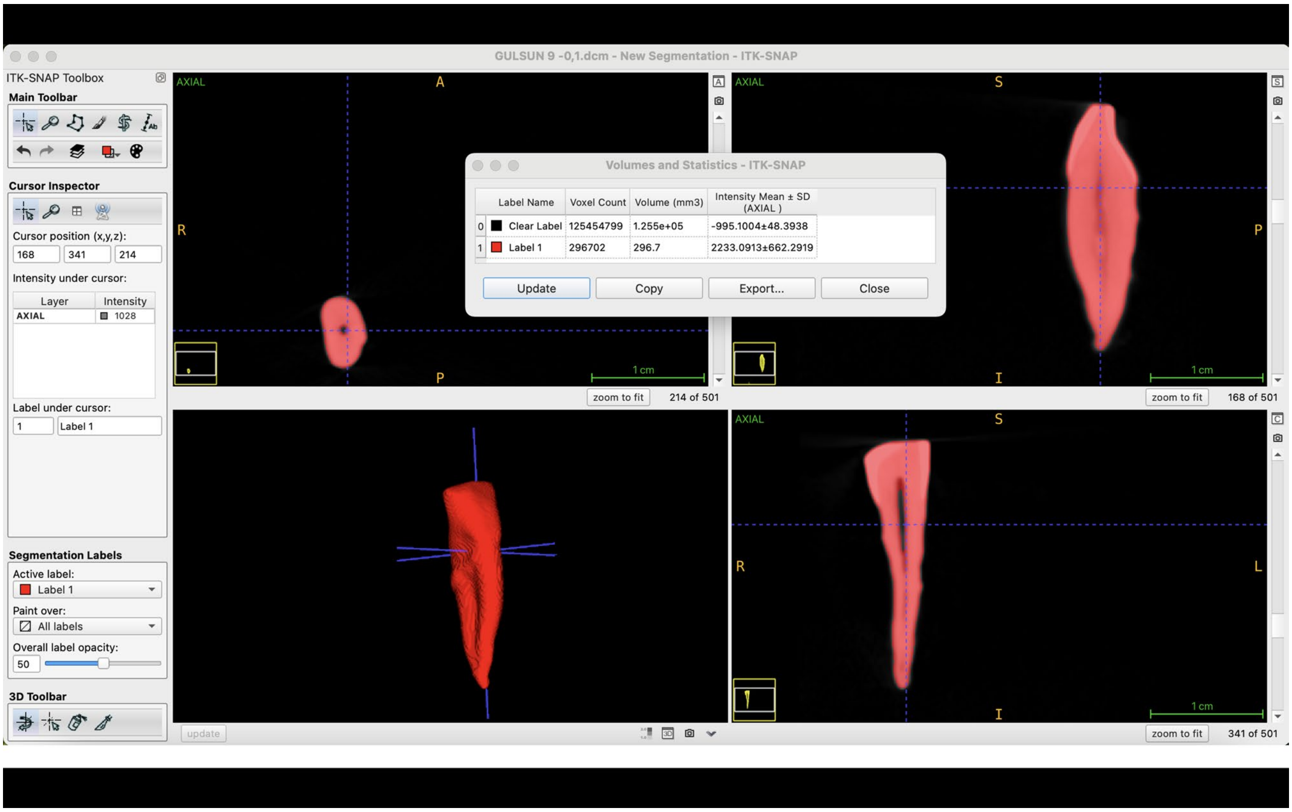

Fig. 2 Volumetric analysis with semi-automatic segmentation in the ITK-SNAP program, 0.1-mm voxel size

Table 1 Descriptive statistics of tooth volume measurements obtained using different CBCT devices, segmentation software, and voxel sizes

Device	Software	Voxel size	Mean	Std. Dev.	Median	Min	Max
Planmeca Promax 3D-Mid	3D Slicer	0.1 mm	356.196	150.587	302.460	185.43	700.8
		0.2 mm	359.228	158.277	288.180	175.55	741.12
	ITKSnap	0.1 mm	376.914	155.510	313.100	197.20	754.10
		0.2 mm	376.633	157.907	322.750	193.00	737.50
Newtom 5G-XL	3D Slicer	0.1 mm	372.316	157.345	295.325	211.11	737.79
		0.2 mm	365.000	152.657	293.570	206.05	722.80
	ITKSnap	0.1 mm	376.339	167.608	298.275	206.80	785.90
		0.2 mm	372.012	165.483	294.950	197.80	763.40
WDM			339.670	126.912	280.00	210.00	650.00

Std. Dev.: Standard Deviation, WDM: Water displacement method

Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics (version 23). The normality of data was analyzed using the Shapiro-Wilk goodness of fit test. The assumption of sphericity was tested using Mauchly's test. For variables that violated this assumption, Epsilon-adjusted p-values were used. A repeated-measures Analysis of Variance (ANOVA) was conducted to examine the effects of voxel size, segmentation software, and CBCT device on volumetric accuracy. Both main effects and interaction terms were evaluated. A p-value of less than 0.05 was considered statistically significant.

Results

Table 1 presents the mean, standard deviation, median, minimum, and maximum tooth volume measurements obtained from different voxel sizes, software, and CBCT devices. Additionally, differences from the gold-standard WDM are summarized in Table 2.

Effect of CBCT device, software, and voxel size

The results of repeated measures ANOVA are shown in Table 3. There was no statistically significant difference observed between the CBCT devices regarding their deviation from the gold standard WDM ($p = 0.431$). However, statistically significant differences were observed

Table 2 Descriptive statistics for deviations from the water displacement method

Device	Software	Voxel size	Mean	Std. Dev.	Median	Min	Max
Planmeca Promax 3D-Mid	3D Slicer	0.1 mm	16.529	44.548	19.935	-74.57	94.19
		0.2 mm	19.561	50.941	25.055	-80.86	91.12
	ITKSnap	0.1 mm	37.247	47.535	38.400	-52.80	120.90
		0.2 mm	36.966	52.112	36.050	-67.00	119.80
Newtom 5G-XL	3D Slicer	0.1 mm	32.649	49.904	32.885	-93.53	119.86
		0.2 mm	25.333	46.867	24.805	-99.77	93.24
	ITKSnap	0.1 mm	36.672	57.282	39.595	-88.88	138.85
		0.2 mm	32.345	55.476	33.190	-99.90	149.40

Std. Dev.: Standard Deviation

Table 3 Results of repeated measures ANOVA regarding the effects of voxel, software, and device on the deviation from the water displacement method

Terms	Factors	Multiple comparisons†			*p*-value
Main effects	Device				0.431
	Software	3D Slicer^{A}	ITKSnap^{B}	WDM^{A}	**0.000***
	Voxel size				0.070
Two-way interactions	Device-Software	Planmeca-3D Slicer^{A}	Planmeca -ITKSnap^{B}	WDM^{A}	**0.000***
		Newtom-3D Slicer^{A}	Newtom-ITKSnap^{B}	WDM^{C}	
	Device-Voxel size	Planmeca-0.1mm^{A}	Planmeca – 0.2mm^{B}	WDM^{A}	**0.001***
		Newtom-0.1mm^{A}	Newtom-0.2mm^{B}	WDM^{C}	
	Software-Voxel size				0.944
Three-way interaction	Device-Software-Voxel size				0.121

†: Bonferoni Post Hoc Test, groups sharing the same superscript do not differ *: statistically significant at 0.05

Planmeca: Planmeca Promax 3D-Mid; Newtom: Newtom 5G-XL; WDM: Water displacement method

between the segmentation software ($p < 0.001$) and in the interaction effects of device-software ($p < 0.001$) and device-voxel size ($p = 0.001$).

Pairwise comparisons revealed that measurements obtained with the Planmeca Promax 3D-Mid device at 0.1 mm voxel size using the 3D Slicer software were closest to WDM ($p = 0.280$). In contrast, other conditions showed significant deviations from WDM. ITK-SNAP software yielded consistently higher volume measurements compared to both 3D Slicer and WDM, regardless of device and voxel size.

The segmentation software significantly affected volumetric deviations, while the CBCT device and voxel size had no significant effect overall.

Figure 3 presents a graphical summary of the distribution of volumetric measurements obtained from two different CBCT devices and two segmentation software programs, alongside the WDM, using multiple boxplots. The 3D Slicer software appears to yield values that are closer to the WDM compared to ITK-SNAP, a finding supported by the statistical analyses described above.

Impact of voxel size

No statistically significant difference was found between the 0.1 mm and 0.2 mm voxel sizes in terms of overall volume deviations ($p = 0.070$). However, subgroup analyses indicated that the most accurate volumetric results were obtained with a 0.1 mm voxel size when using the 3D Slicer software on the Planmeca Promax 3D-Mid device.

Although not statistically significant, the 0.1 mm voxel size yielded the most accurate volumes, especially with 3D Slicer.

Inter-observer and intra-observer reliability

Inter-observer reliability, assessed using the intraclass correlation coefficient (ICC), ranged between 0.995 and 0.999, indicating excellent agreement. Intra-observer agreement ranged from 0.893 to 0.997, confirming high reproducibility.

Both inter- and intra-observer agreements were excellent, confirming the reproducibility of segmentation.

These findings suggest that segmentation software selection plays a more critical role in volumetric accuracy than voxel size or CBCT device choice.

Discussion

With the advancement of digital technology, major developments have occurred in the field of dental radiology over the past two decades. CBCT has become widely adopted due to its superior spatial resolution. A process known as segmentation is applied to CBCT images for three-dimensional volume analysis. This procedure enables the segmentation of structures such as the jaws, paranasal sinuses, and teeth. In forensic dentistry, tooth segmentation is utilized for age estimation, while in

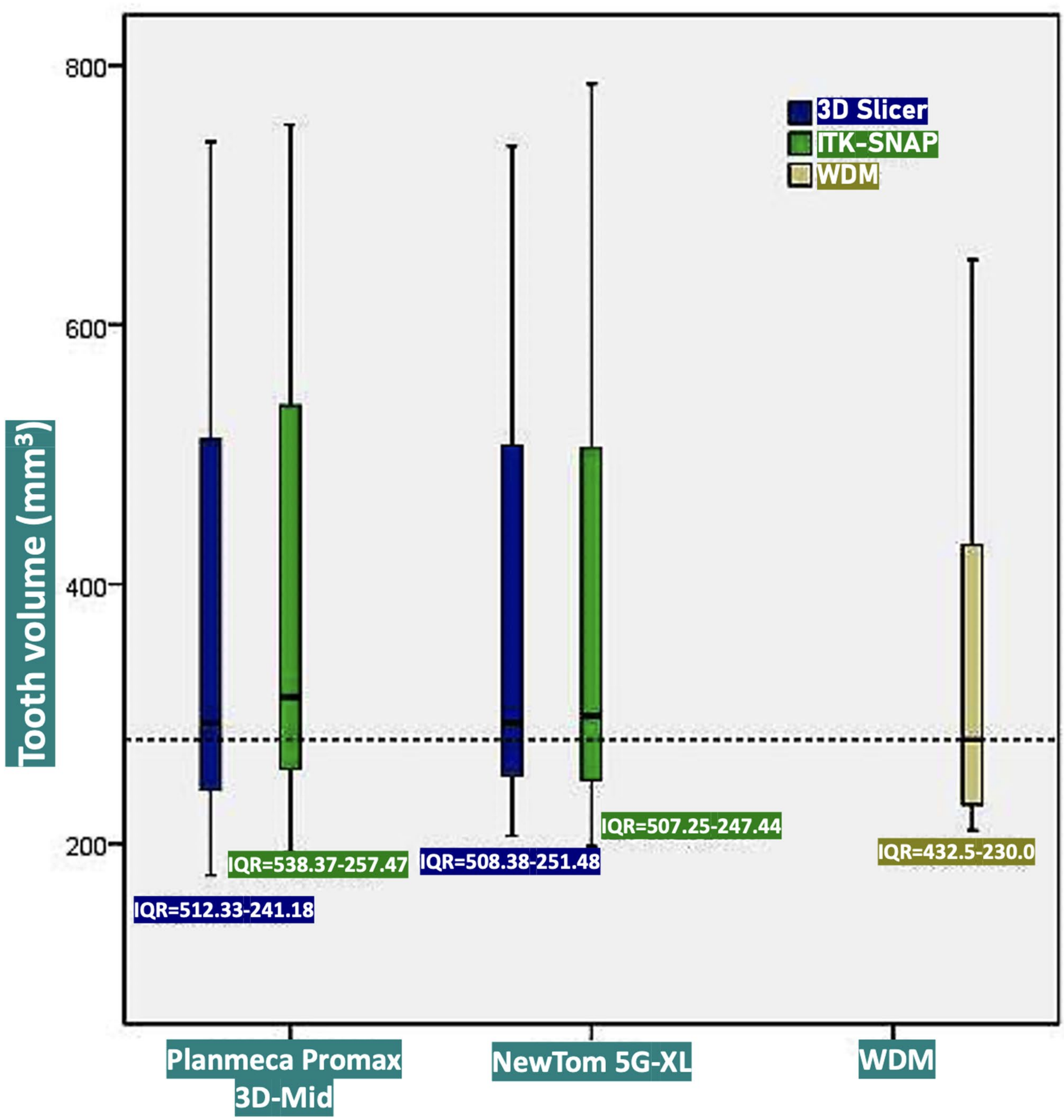

Fig. 3 Distributions of volumes measured at 0.1-mm voxel size. Boxplot comparison of volume measurements obtained using different software and imaging systems. Planmeca Promax 3D-Mid and NewTom 5G-XL datasets were segmented using 3D Slicer (blue) and ITK-SNAP (green), while WDM (beige, water displacement method) refers to volume estimation. The boxes represent interquartile ranges (IQR), the lines inside the boxes indicate the median values, and the whiskers show the minimum and maximum values

clinical settings, it assists in planning procedures such as auto-transplantation [4, 12, 13].

Given its optimal balance between efficiency and accuracy, semi-automatic segmentation was selected for this study, as previously discussed. This method is frequently preferred in similar studies, as it enables rapid data collection with high reliability [1]. Numerous segmentation programs are available in the market. A recent study by Aydogdu et al. demonstrated that different segmentation programs can affect tooth volumetric measurements [4]. That study used four different software programs and reported a statistically significant difference between measurements obtained with 3D Doctor and those with WDM. Considering this, our study aimed to evaluate whether two widely used and freely available segmentation programs—3D Slicer and ITK-Snap—produced differences in volume measurements. A statistically significant difference was found between the two programs. Specifically, ITK-Snap yielded higher volume deviations than both 3D Slicer and the gold standard WDM.

Given the growing number of segmentation tools, it is important for clinicians to select the appropriate program based on their intended clinical or research application. Most previous studies on tooth volumetric measurements have focused on single-rooted incisors. The reported volumes for these teeth ranged from 465 mm^3 to 609 mm^3 when using various programs [4, 14–16]. In our study, the average tooth volume was calculated as 339.6 mm^3, a value lower than previously reported. We believe this discrepancy is attributable to the smaller size of central and lateral incisors compared to canines, as well as the relatively low number of canines included in our sample.

Voxel size is another critical parameter that affects volumetric measurements. Larger voxel sizes are associated with reduced measurement accuracy [1, 6]. Increases in voxel size also correlate with decreases in both inter-class reliability and intra-observer reproducibility [1]. Segmentation studies involving various anatomical structures—such as the jaws, maxillary sinuses, airways, teeth, and pulp—have employed images with a range of voxel sizes [1, 4, 17–19]. Dong et al. examined pig mandibles using four voxel sizes (0.125-mm, 0.2-mm, 0.3-mm, and 0.4-mm), and found that the deviation rate increased as voxel size increased [17]. Similarly, Maret et al. reported that while voxel sizes up to 0.2-mm did not affect measurement reliability, measurements became less reliable with voxels of 0.3-mm or larger [18].

However, not all studies agree on this point. For instance, Sang et al. reported no significant difference in volume measurements between voxel sizes of 0.15-mm and 0.3-mm [19]. Likewise, Ozdede et al. found no statistically significant difference in volume measurements at voxel sizes of 0.1-mm, 0.2-mm, and 0.4-mm [1]. These divergent findings may be due to differences in the anatomical structures studied, segmentation methods used, software programs employed, and CBCT devices utilized. One of the objectives of our study was to address these variations and help guide the selection of appropriate measurement methodologies. According to our results, voxel sizes of 0.1-mm and 0.2-mm did not significantly affect volumetric measurements.

When comparing deviation rates from the gold standard, previous studies have shown that deviations vary depending on the segmentation program and voxel size used [3, 4]. For instance, Liu et al. used the Amira software to compare digital and physical volume measurements of premolars and reported a volume deviation rate between 4 and 7% [3]. However, their study was conducted on patient images acquired from different devices and voxel sizes, which may have influenced standardization. Aydogdu et al. compared tooth volumes using 3D Doctor, 3D Slicer, ImageJ, and ITK-Snap software at voxel sizes of 0.3-mm and 0.4-mm [4]. Their findings indicated a higher deviation rate with larger voxel sizes; the deviation was −15.7% with 0.4 mm voxels in 3D Doctor and +15% with 0.4 mm voxels in ITK-Snap.

In our study, deviation rates similarly ranged from 4.9 to 11.0%. The minimal deviation from the gold standard was recorded in measurements obtained using the Planmeca Promax 3D-Mid device at a 0.1 mm voxel size in combination with the 3D Slicer software. We believe the use of smaller voxel sizes contributed to the lower deviation rates compared to previous studies. These findings align with the consensus that reducing voxel size improves volumetric measurement accuracy [1].

CBCT image quality is influenced by multiple factors, including exposure settings, patient positioning, volume reconstruction techniques, and DICOM export protocols. These elements collectively impact the accuracy of volumetric assessments [12]. Given the increasing number of CBCT devices on the market and variations in their technical specifications, several studies have investigated whether device-related differences affect volumetric accuracy [5, 12, 20]. For example, Shaheen et al. evaluated three CBCT systems (Accuitomo 170, Scanora 3D, and Planmeca Promax) and found that all yielded highly accurate volume measurements compared to the WDM [12]. Similarly, our study revealed no statistically significant difference between the Planmeca Promax 3D-Mid and NewTom 5G-XL devices, likely due to the inherently high geometric accuracy of CBCT systems. These findings suggest that device selection may not significantly influence volumetric measurement reliability.

The findings of this study have meaningful clinical implications. While neither CBCT device type nor voxel size significantly affected volumetric accuracy for single-rooted teeth, the choice of segmentation software had a substantial impact. This underscores the importance of software selection, especially when working with voxel sizes between 0.1-mm and 0.2-mm. Clinicians performing volumetric analyses—whether for endodontic planning, orthodontic assessment, or implant preparation—should be aware that software choice can directly influence clinical outcomes.

The consistently higher volume measurements obtained via ITK-SNAP may be attributed to its semi-automated region-growing algorithm, which initiates segmentation from seed points and includes surrounding voxels based on intensity. In cases of ambiguous grayscale transitions, this may result in over-segmentation and subsequent volume overestimation. In contrast, 3D

Slicer permits more precise threshold-based segmentation and manual refinements, yielding more conservative and anatomically accurate results. Awareness of such algorithmic differences is essential when selecting software for clinical or forensic applications. For instance, in forensic dentistry—where accurate volume estimation is critical for age estimation or personal identification—validated software such as 3D Slicer may enhance measurement reliability.

Limitations

This study has several limitations. First, only single-rooted incisor teeth were examined. These teeth generally have relatively simple and uniform root canal morphology, which facilitates segmentation and reduces partial volume effects. However, multi-rooted teeth—such as molars or premolars—often exhibit complex root configurations, overlapping structures, and denser root canal systems. These anatomical complexities could affect both the segmentation performance and the volumetric accuracy of CBCT, particularly when using semi-automatic methods. Therefore, the findings of this study may not be directly generalizable to more anatomically complex tooth types.

Second, only two CBCT systems (Planmeca Promax 3D-Mid and NewTom 5G-XL) were used. Although these devices are widely recognized and clinically validated, there are numerous other CBCT models with different reconstruction algorithms, radiation settings, and image quality parameters that may influence volumetric measurements. Future studies incorporating a wider range of CBCT devices could reveal device-specific biases or variability in segmentation accuracy.

Third, while 3D Slicer and ITK-SNAP are reputable and widely-used segmentation programs, they represent only a subset of the available tools. Other commercial or AI-assisted segmentation platforms may offer different algorithms (e.g., deep learning, automatic edge detection), which could impact the precision and consistency of measurements. Therefore, results may vary if alternative software programs or automation levels are employed. Including such platforms in future research would help improve the robustness and clinical translatability of CBCT volumetric assessment protocols.

Conclusion

This study demonstrated that CBCT device selection (Planmeca Promax 3D-Mid vs. NewTom 5G-XL) and voxel size (0.1-mm vs. 0.2-mm) had no statistically significant effect on volumetric measurements of single-rooted incisor teeth. However, segmentation software choice critically influenced accuracy: 3D Slicer provided results with the lowest deviation from the gold standard WDM, while ITK-SNAP consistently overestimated volumes. The most precise protocol combined the Planmeca Promax 3D-Mid device, 0.1-mm voxels, and 3D Slicer software. These findings underscore that software selection is paramount for reliable CBCT-based volumetry in clinical applications, though both 0.1-mm and 0.2-mm voxel protocols remain viable when paired with validated tools. Future studies should investigate multi-rooted teeth and automated segmentation to enhance generalizability.

Acknowledgements
Not applicable.

Author contributions
Conceptualization: [Melih Ozdede, Gulsun Akay]; Methodology: [Melih Ozdede, Gulsun Akay, Ozge Karadag Atas]; Formal analysis and investigation: [Melih Ozdede, Gulsun Akay, Ozge Karadag Atas]; Writing - original draft preparation: [Melih Ozdede, Gulsun Akay, Ozge Karadag Atas]; Review and editing: [Gulsun Akay, Melih Ozdede, Ozge Karadag Atas].All authors have reviewed and approved the final version of the manuscript.

Funding
Not applicable.

Data availability
The entire data analyzed in this study has been included in a published article. The corresponding author will provide access to the raw data upon reasonable request.

Declarations

Ethics approval and consent to participate
The study received ethical approval from Pamukkale University's Non-Interventional Clinical Research Ethics Committee (Date: 15.04.2021, No: E-60116787-020-44426).

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Human rights statement
All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2008.

Informed consent
Informed consent was obtained from the participants for inclusion in the study.

Received: 18 March 2025 / Accepted: 18 June 2025
Published online: 02 July 2025

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