

Article

Influence of Sub-200 μm CBCT Voxel Size on Assessment of Root Canal Anatomy: A Cadaver Study

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Simple Summary

It is recommended that cone-beam computed tomography (CBCT) scans for endodontic (root canal) therapy should be taken at voxel sizes of 200 μm or smaller when assessing root canal anatomy. However, it is unclear whether there are differences in the diagnostic accuracy between different sub-200 μm voxel reconstructions. Hence, this study was conducted to compare scans taken at 80 μm , 125 μm and 160 μm . The findings indicated that the highest resolution scans (80 μm) were not statistically significantly better than the 125 μm scans, but were considerably better than the 160 μm scans in identifying fine anatomical structures. However, while all of the CBCT scans accurately identified simple root canal anatomy, they were not as predictable for more complex root canal anatomy. Future studies should include larger numbers of teeth with complex anatomy and simulated patient movement to add to the knowledge base and to lead to more definitive clinical recommendations of preferred voxel sizes.

Abstract

The aim of this study was to compare the accuracy of different sub-200 μm voxel reconstruction of CBCT scans in the identification of root canal anatomy. Cadaveric dentate maxillae and mandibles with soft tissues attached (69 teeth comprising 91 roots) were assessed with scans reconstructed at voxel sizes of 80 μm , 125 μm , and 160 μm . Three examiners recorded the canal configuration, presence of lateral canals, PAI score, and image quality seen on the scans. Micro-computed tomography (micro-CT) scans of the specimens reconstructed at 10 μm served as the reference standard. There was no significant difference between 80 μm and 125 μm reconstructions, but 80 μm scans were more accurate than 160 μm scans ($p = 0.04$). The findings suggest that canal anatomical complexity may have a greater influence on diagnostic accuracy than differences among the sub-200 μm voxel reconstructions evaluated. Lateral canals were only noted in 2% of roots in CBCT scans, but were present in 55% of roots assessed with micro-CT. There was significantly more variation in the assessment of image quality for 80 μm compared with 125 μm ($p = 0.01$) and 160 μm ($p = 0.003$) scans. Generally, 80 μm reconstructions provided marginally improved diagnostic yield compared with 160 μm scans; however, CBCT scans showed limited accuracy for more complex canal configurations. The poorer image quality of 80 μm scans may be due to the limited field of view, which causes partial volume effects rather than being reconstructed at 80 μm per se.

Keywords: canal anatomy; field of view; micro-CT; resolution



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1. Introduction

Radiography is an essential part of endodontic diagnosis, treatment planning, intraoperative assessment of treatment progress, and follow-up of healing outcomes. Conventional radiographs are the mainstay of imaging, but suffer from drawbacks including geometric distortion and superimposition of anatomical structures. For example, accuracy may be lower when assessing complex canal anatomy [1,2], or detection of periapical lesions if the overlying bone is dense [3]. Furthermore, there can be significant inter- and intra-examiner variability [4,5].

Cone-beam computed tomography (CBCT) is a three-dimensional imaging modality that can provide additional information. Indications include preoperative assessment of complex root canal morphology (e.g., C-shaped canals), identification of missed canals, assessment of pathosis such as root resorption, and pre-surgical evaluation of anatomy [6]. Root canal anatomy is commonly classified according to the Vertucci classification system, which describes the number and configuration of canals from the pulp chamber to the apex. While Vertucci Type I anatomy consists of a single canal extending from chamber to apex, more complex configurations involve bifurcation, rejoining, or multiple independent canals. Accurate identification of these complex canal systems is clinically important because untreated canals or canal divisions are associated with persistent infection and endodontic treatment failure. As canal complexity increases, accurate radiographic interpretation becomes progressively more challenging because fine canal bifurcations and isthmuses approach the spatial resolution limits of CBCT imaging. CBCT imaging should be reserved for select cases because it is associated with a higher radiation dose compared with conventional imaging, with up to 60 μSv for a small field-of-view (FOV) scan [7] compared with 5 μSv for digital radiographs [8].

At present, there are few clinical guidelines regarding the optimal parameters for CBCT imaging. Maximum voxel thresholds of 200 μm [9] to 300 μm [6] have been recommended for endodontic purposes; however, the guidelines are unclear as to whether smaller voxel reconstructions provide diagnostic advantages. Smaller voxel sizes may not necessarily provide a better image quality because movement artefacts may be more apparent [10] and there may be more image noise [11]. On the other hand, larger voxel sizes may be associated with partial volume averaging artefacts, which occur when the voxel size is larger than the structure being imaged. Although epidemiological studies have used CBCT to investigate canal morphology, these studies have involved a range of voxel sizes, FOVs and CBCT platforms, making comparisons difficult. Furthermore, no previous study has systematically compared multiple sub-200 μm CBCT reconstructions obtained under clinically realistic cadaveric conditions with intact soft tissues using micro-CT as the reference standard. Consequently, it remains unclear whether progressively smaller voxel reconstructions provide meaningful improvements in the assessment of increasingly complex root canal anatomy.

The primary aim of this study was to compare the differences in the amount of diagnostic information gathered using different levels of high-resolution CBCT. The null hypothesis was that there was no difference in the assessment of canal anatomy between 80 μm , 125 μm , and 160 μm scans, using micro-CT as the reference standard. Secondary aims were to assess the impact of voxel size on interpretation of the CBCT PAI score and perceived image quality.

2. Materials and Methods

Ethical approval was granted by the Health Sciences Human Ethics Advisory group of the University of Melbourne (Ethics ID:1956010.1). Dentate cadavers with soft tissues attached fixed in 5% formalin were sourced through the University of Melbourne Anatomy

Department. The sample comprised 69 teeth (Table 1), obtained from two complete maxillae, one partial maxilla, three complete mandibles and one partial mandible. No formal a priori sample size calculation was performed because the number of suitable cadaveric specimens was limited by availability through the University of Melbourne Anatomy Department. However, the sample size was comparable to those reported in previous ex vivo CBCT studies investigating root canal morphology [12–15].

Table 1. Summary of sample composition stratified into tooth types. Numbers in brackets indicate samples damaged during jaw sectioning and not scanned with micro-CT. These teeth were excluded from analysis assessing accuracy of CBCT scans relative to micro-CT but included for all other analyses.

Tooth Type	Number of Teeth	Number of Roots
Maxillary incisors	12 (1)	12 (1)
Maxillary canines	4 (1)	4 (1)
Maxillary premolars	5 (1)	7 (2)
Maxillary molars	8	20
Mandibular incisors	12	12
Mandibular canines	7 (2)	7 (2)
Mandibular premolars	13	13
Mandibular molars	8	16
Total	69 (5) teeth	91 (6) roots

2.1. CBCT

Specimens were placed into plastic containers and fully immersed in 0.4% thymol solution. CBCT scans were performed using the 3D Accuitomo 170 (J. Morita Mfg Corp. Kyoto, Japan), operated at 90 kV and 8 mA with 360° rotation. The field of views (FOVs) were 40 mm × 40 mm × 40 mm, 60 mm × 60 mm × 60 mm, and 80 mm × 80 mm × 80 mm, which were reconstructed at voxel sizes of 80 µm, 125 µm, and 160 µm respectively. There were 27 scans performed per FOV, resulting in a total of 81 CBCT scans.

Examiners were blinded in three ways. Firstly, the scans of the same region reconstructed resolutions were opened simultaneously in the Horos 4.0 CBCT viewing software (Horos Project, Annapolis, MD, USA), with the “Zoom sync” function which synchronizes the degree of zoom between scans of different FOVs. An identical area of interest was selected in each scan with the circular selection tool, and areas outside the region of interest were set to a grey value of −10,000 so structures were displayed at identical sizes and with the same amount of surrounding tissue to blind examiners to the FOV used. Secondly, three orthogonal reconstructions (coronal, sagittal, axial) from each scan were exported as .mov files at the minimum slice thickness (i.e., 80 µm, 125 µm, 160 µm slice thickness for the three voxel reconstructions) at a rate of 1 frame per second. Videos were chosen over static images because it allowed for the maximum number of sections to be viewed, and it simulated scrolling through scans on CBCT software, thereby making the viewing experience more clinically relevant. The sagittal and coronal views were aligned to coincide with the long axis of the tooth closest to the centre of the scan, and the axial views were aligned along the long axis of the teeth. As the sagittal or coronal views may not have been coincident with the long axis of every canal, especially in teeth with multiple divergent roots or significant canal curvatures, this was controlled for by limiting the teeth shown to those with the same long axis orientation and providing three orthogonal views. Brightness and contrast settings were standardized across all examinations. The order of the videos was randomized using the random number generator feature in Excel Version 16.46 (Microsoft Corp, Redmond, WA, USA).

CBCT scans were assessed by three calibrated examiners, comprising one third-year endodontic postgraduate student and two endodontists with 16–39 years' experience in specialist endodontic practice. The examiners recorded the canal configuration, presence of lateral canals, CBCT PAI score in the sagittal and coronal slices [3] and assigned a score to the image quality (Figure 1) using a standardized data entry form. The CBCT PAI score in the sagittal and coronal slices were averaged to provide a single PAI score to facilitate statistical analysis. Average PAI scores that differed by less than 1 were considered equivalent as the difference was deemed clinically insignificant.

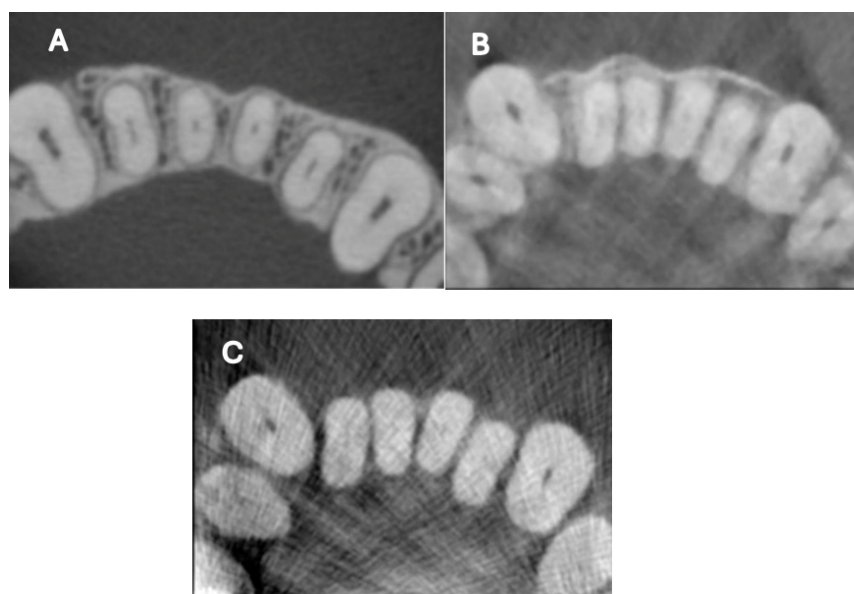


Figure 1. Examples of image quality provided to examiners during training showing (A) score 1—good image quality, (B) score 2—moderate image quality, (C) score 3—poor image quality.

The examiners were calibrated using ten CBCT scans from the sample, with the distribution of anterior and posterior teeth reflective of the overall sample. Adequate calibration was defined as an inter-examiner weighted kappa score of at least 0.60. The examiners independently assessed each scan before discussing discrepancies to ensure consistent interpretation of the assessment criteria. The level of intra-observer agreement was determined by reassessing 20% of the sample two months after initial evaluation. Inter-observer and intra-observer agreement for CBCT PAI scores were calculated using weighted Kappa scores. Weighted scoring was chosen as small differences are unlikely to be clinically significant (e.g., PAI score of 1 vs. 2). Inter-observer and intra-observer agreements for other parameters were calculated using unweighted Kappa scores.

2.2. Micro-CT

The teeth and surrounding alveolar bone were sectioned from the basal bone using handsaws and diamond discs mounted in a laboratory motor. The teeth were suspended in Eppendorf tubes containing 0.4% thymol and stabilized with polystyrene wedged between the tooth and the container wall to prevent movement during scanning. Specimens were stored at 4 °C until ready for micro-CT scanning.

The specimens were mounted on the micro-CT stage within inverted falcon tubes glued to a glass rod with five minutes allowed to elapse before scanning to allow for settling of any suspended debris. The scans were performed using a Phoenix Nanotom M micro-CT scanner (Waygate Technologies, Wunstorf, Germany) operated at 120 kV, 250 μ A, with 0.5 mm aluminum and 0.1 mm copper filters to pre-harden the X-ray. The data were reconstructed at 10 μ m with a beam hardening correction algorithm, inline

median filter, and ring-artefact correction filter applied using the datos1x reconstruction software (Waygate Technologies). Due to the small FOV at this resolution, two or three scans (depending on root length) were taken of each tooth at different corono-apical levels and combined to allow visualization of the entire root. The scans were viewed using Fiji (ImageJ, version 1.53; U.S. National Institutes of Health, Bethesda, MD, USA) [12] operated through a high-performance computing cluster operating on the Linux operating system, with each tooth reconstructed in three orthogonal views.

A linear mixed effects model was used due to non-independence of the data, with repeated measurements made on the same samples. The resolution was set as the fixed effect, and examiner and sample ID as random effects. It was used to assess the association between voxel size and odds of agreement with the micro-CT result for canal configuration and between pairs of assessments for canal configuration, CBCT PAI score, and image quality. Canal configurations were stratified into Vertucci Type I and non-Vertucci Type I [13] to facilitate statistical analysis due to heterogeneity in configurations present in the latter category. Several individual Vertucci configurations occurred infrequently within the sample, precluding statistically meaningful analysis of each configuration separately. Accordingly, non-Type I configurations were combined to provide sufficient statistical power while allowing comparison between simple and more complex canal anatomy.

3. Results

3.1. Accuracy of CBCT for Canal Anatomy Assessment

A Vertucci Type I configuration was the most common canal type noted on micro-CT scans, comprising 64.8% of roots ($n = 55$) in the sample (Table 2).

Table 2. Specific canal configurations noted in CBCT and micro-CT scans; results for all voxel sizes combined. Agreement between micro-CT and CBCT in **bold**.

		CBCT Canal Classification								Number of Roots *	Percentage CBCT Correct
		1	1-2	1-2-1	1-3	2	2-1	2-1-2	2-1-2-1		
Micro-CT	1	480	0	11	1	0	3	0	0	55	97.0%
	1-2	108	11	2	0	0	9	2	0	15	8.1%
	1-2-1	4	4	28	0	0	0	0	0	4	77.8%
	1-2-1-2	7	1	1	0	1	7	1	0	2	0%
	2	0	0	0	0	0	9	0	0	1	0%
	2-1	9	0	1	0	0	44	0	0	6	81.5%
	2-1-2	6	0	0	0	0	3	0	0	1	0%
	2-1-2-1	1	0	0	0	0	7	0	1	1	11.1%

* Total number of roots with a particular configuration as assessed with micro-CT. Calculated by summing each row and dividing by 9 (each root was examined by 3 examiners, with each examiner assessing 3 different resolutions; therefore, there was a total of 9 observations per root and a total of 765 observations for 85 roots).

Using micro-CT as the reference standard (see example in Figure 2), the mean percentage of correct assessments using CBCT was 97.0% for Vertucci Type I configurations (98.2% for 80 μm , 96.3% for 125 μm , and 96.3% for 160 μm), compared with 31.1% for other canal configurations (32.3% for 80 μm , 32.2% for 125 μm , and 28.9% for 160 μm) (Table 3).

Correct identification was significantly more likely for Vertucci Type I anatomy ($p < 0.001$), remaining consistently high across all voxel sizes (96.3–98.2%), whereas accuracy for non-Type I configurations was substantially lower (28.9–32.3%). This indicates that canal complexity had a much greater influence on diagnostic performance than the relatively small differences observed between voxel reconstructions. The inter-examiner agreement was moderate, and the intra-examiner agreement was moderate to excellent (Table 4).

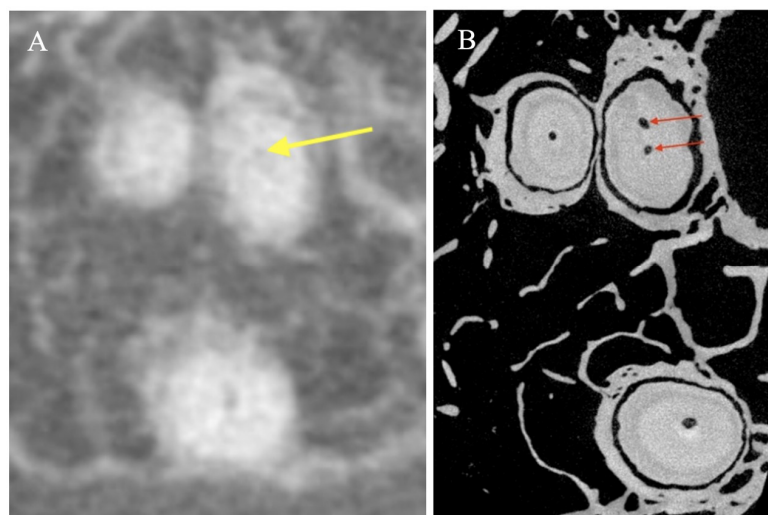


Figure 2. Scan of tooth 18 taken with (A) CBCT at 80 µm resolution and (B) micro-CT at 10 µm resolution. The CBCT scan appears to show a single canal in the mesio-buccal root (yellow arrow), whereas the micro-CT scan shows two canals (red arrows).

Table 3. Number of correct observations of canal anatomy with CBCT, stratified into canal configurations. Each root was classified at three resolutions, and at each resolution by three different examiners, resulting in a total of 765 comparisons from 85 roots.

	CBCT Classification of Canal Anatomy	
	Vertucci Type I	Other Configurations
Correctly identified on CBCT compared to micro-CT	80 µm: 162	80 µm: 29
	125 µm: 159	125 µm: 29
	160 µm: 159	160 µm: 26
	<u>480</u>	<u>84</u>
Incorrectly identified on CBCT compared to micro-CT	80 µm: 3	80 µm: 61
	125 µm: 6	125 µm: 61
	160 µm: 6	160 µm: 64
	<u>15</u>	<u>186</u>
Total:	Vertucci type I on micro-CT: 495 (97.0% correctly identified with CBCT)	Other configurations on micro-CT: 270 (31.1% correctly identified with CBCT)

Table 4. Intra-examiner and inter-examiner reliability for assessment of parameters. Qualitative descriptions of the strength of agreement, where a kappa score of 0–0.2 = no agreement, 0.21–0.39 = minimal agreement, 0.40–0.59 = weak agreement, 0.60–0.79 = moderate agreement, 0.80–0.90 = strong agreement, above 0.90 = almost perfect agreement.

	Kappa Value
Canal configuration	
Intra-examiner reliability ^a	
Examiner 1	1
Examiner 2	0.62
Examiner 3	0.82
Inter-examiner reliability ^a	
80 µm	0.80
125 µm	0.75
160 µm	0.75

Table 4. *Cont.*

	Kappa Value
CBCT PAI score	
Intra-examiner reliability ^a	
Examiner 1	0.90
Examiner 2	0.88
Examiner 3	0.74
Inter-examiner reliability ^b	
80 µm Examiner 1 vs. 2	0.93
80 µm Examiner 1 vs. 3	0.86
80 µm Examiner 2 vs. 3	0.90
125 µm Examiner 1 vs. 2	0.90
125 µm Examiner 1 vs. 3	0.81
125 µm Examiner 2 vs. 3	0.82
160 µm Examiner 1 vs. 2	0.86
160 µm Examiner 1 vs. 3	0.78
160 µm Examiner 2 vs. 3	0.81
Image quality	
Intra-examiner reliability ^a	
Examiner 1	0.50
Examiner 2	−0.047
Examiner 3	0.21
Inter-examiner reliability ^a	
80 µm	0.66
125 µm	0.34
160 µm	0.26

^a Light's kappa; ^b Weighted Cohen's kappa.

Pairwise comparison showed no significant differences between 80 µm and 125 µm reconstructions and 125 µm and 160 µm scans (Table 5). The 80 µm scans were significantly more accurate than the 160 µm scans. Thus, the null hypothesis that there was no difference in the assessment of canal anatomy between 80 µm, 125 µm, and 160 µm scans was rejected.

Table 5. Pairwise comparison showing effect of voxel size on likelihood of identifying the canal configuration using micro-CT as the reference standard. Significance was set at $p < 0.05$.

	Odds Ratio	95% Confidence Interval	p-Value
Canal configuration			
80 µm vs. 125 µm	3.00	0.66–13.69	0.16
80 µm vs. 160 µm	4.81	1.04–22.27	0.04
125 µm vs. 160 µm	3.00	0.41–6.21	0.49

There was very low sensitivity for lateral canals in all CBCT scans, with lateral canals and apical deltas detected in 55% of roots using micro-CT, but only noted in two roots in the CBCT scans.

3.2. CBCT PAI Score

The voxel size did not have any significant impact on the CBCT PAI score assigned (Table 6). Both the inter-examiner and intra-examiner agreement were rated as moderate to excellent (Table 4).

Table 6. Pairwise comparison showing effect of voxel size on likelihood of examiners agreeing with each other for assessment of canal configuration, CBCT PAI score, and image quality. Significance was set at $p < 0.05$.

	Odds Ratio	95% Confidence Interval	<i>p</i> -Value
Canal configuration			
80 μm vs. 125 μm	1.77	0.69–4.57	0.24
80 μm vs. 160 μm	1.60	0.62–4.11	0.38
125 μm vs. 160 μm	0.90	0.36–2.24	0.82
CBCT PAI score			
80 μm vs. 125 μm	2.04	0.57–7.31	0.27
80 μm vs. 160 μm	1.80	0.50–6.47	0.36
125 μm vs. 160 μm	0.90	0.23–3.29	0.85
Image quality			
80 μm vs. 125 μm	0.16	0.045–0.60	0.01
80 μm vs. 160 μm	0.14	0.037–0.51	0.003
125 μm vs. 160 μm	0.84	0.30–2.37	0.73

3.3. Image Quality

There were few scores of “3” noted; therefore, the scores of “2” and “3” were combined to facilitate statistical analysis. There was strong evidence of a difference in odds between the resolutions for assessment of image quality, with 80 μm being more likely to be perceived as having more noise and/or artefacts (Table 6). The inter-examiner agreement was rated as minimal to moderate, and the intra-examiner agreement was rated as none-to-weak (Table 4).

3.4. Effect of Voxel on Agreement Between Examiners

With regard to the effect of voxel size on the likelihood of inter-examiner agreement, there were no significant differences between 80 μm , 125 μm and 160 μm reconstructions for assessment of the canal anatomy and CBCT PAI score. In other words, the voxel size did not influence the rate of inter-examiner agreement. By contrast, interpretation of image quality was highly variable and dependent on voxel size, with interpretation of 125 μm and 160 μm scans showing significantly lower inter-examiner and intra-examiner reliability (Tables 4 and 6).

4. Discussion

Few studies have directly compared multiple sub-200 μm CBCT reconstructions under controlled conditions. The cadaveric model with surrounding soft tissues improved clinical realism compared with studies that neglect replication of the periradicular tissues [14–19], while use of a single CBCT platform reduced variability from proprietary reconstruction algorithms. Canal configuration was selected as the primary outcome because it reflects both spatial and contrast resolution, with micro-CT serving as the reference standard due to its high resolution [20,21]. All three reconstructions showed excellent accuracy for Vertucci Type I anatomy but considerably lower accuracy for more complex canal configurations. These findings suggest that canal anatomical complexity may have a greater influence on diagnostic accuracy than voxel size alone. Although 80 μm reconstructions demonstrated statistically higher diagnostic performance than 160 μm scans (Table 5), the absolute improvement was modest compared with the marked reduction in accuracy associated with increasing canal complexity (Table 3). Canal bifurcations were frequently misclassified as Type I anatomy, likely due to partial volume averaging causing isthmi and bifurcations to appear as a single contiguous canal space. The relatively wide confidence intervals surrounding several odds ratios reflect the modest sample size and indicate some

uncertainty regarding the magnitude of the estimated effects. Consequently, the results should be interpreted with appropriate caution despite the statistically significant findings.

These findings are consistent with previous studies reporting broadly similar performance between sub-200 μm CBCT reconstructions and micro-CT for assessment of canal morphology, particularly in samples dominated by Vertucci Type I anatomy [22,23]. Studies reporting higher agreement often assessed simpler outcomes such as presence of the MB2 canal [24]. Although the primary statistical analyses grouped all non-Vertucci Type I canal configurations together, the descriptive data presented in Table 2 demonstrate considerable variation in diagnostic accuracy among individual complex canal configurations. Some configurations, such as Vertucci Type III and Type V, were identified with relatively high accuracy, whereas others were frequently misclassified as Vertucci Type I anatomy. Formal statistical comparisons between individual configurations were not possible because several categories were represented by only one or two roots. Consequently, these descriptive findings should be interpreted cautiously but suggest that the specific canal morphology may also influence diagnostic performance.

Lateral canals and apical deltas were rarely detected on CBCT scans in the present study. A similar finding was reported for mandibular molars assessed with CBCT scans reconstructed at 200 μm reconstructions [25]. The low detection rate contrasts with an earlier report where 80% of lateral canals were identified on CBCT scans reconstructed at 125 μm reconstructions [19]. This discrepancy may relate to use of extracted teeth rather than cadaveric specimens with surrounding tissues intact resulting in differences in attenuation characteristics, as well as the small voxel size used for reconstruction. Another factor may relate to differences in professional background of the examiners. Experienced oral maxillofacial radiologists have been reported to detect more subtle features such as lateral canals and cracks compared with endodontists and oral maxillofacial radiology registrars [19,26], although extracted tooth models do not simulate clinical reality. In any case, in clinical practice it is usually the endodontist who interprets the root canal anatomy and therefore using examiners with an endodontic background is more clinically relevant.

Although the sample size was modest, it was comparable to previous ex vivo CBCT studies investigating canal morphology [15,17,19,21]. Nevertheless, larger studies enriched with more teeth exhibiting complex anatomy would strengthen future analyses. The results of previous investigations and the present study suggest that CBCT should be used cautiously for interpretation of complex anatomy, even when the highest resolutions are used. The parameters of voxel size and FOV could also not be independently varied using the selected CBCT platform, although in practice these two parameters are correlated in most CBCT systems.

Guidelines recommending a maximum voxel reconstruction size of 200 μm for endodontic purposes are based on evidence that 125–200 μm scans are significantly more accurate than 300–400 μm scans for detection of MB2 canals [9,15]. A systematic review found 200 μm reconstructions were generally more sensitive for detection of simulated pathosis compared with larger voxel sizes [27]. Some studies show no significant differences between low- and high-resolution scans [14,18,28–31]. These should be interpreted with caution as the lack of difference may relate to the experimental set-up. For example, studies that simulated resorptive lesions using burs occasionally noted no significant difference between ≤ 200 μm and 400 μm CBCT scans in detection of these defects [14,18], which most likely relates to the large diameter (>0.5 mm) of the defects created that would be readily detectable even at coarse resolutions. Furthermore, bur-induced cavities have smooth uniform hemispherical outlines that are less prone to partial volume averaging defects and therefore appear well-defined even at larger voxel reconstructions, resulting in overestimation of CBCT sensitivity. Many studies have found no significant differences among

sub-200 μm reconstructions for detection of external and internal resorption [18,32–34], transverse and vertical root fractures [16,30,35–38], and perforations [29,39]. Conversely, a small number of studies report greater sensitivity of sub-100 μm reconstructions for the assessment of vertical root fractures [40,41], and sub-150 μm reconstructions for the evaluation of external resorptive defects [42]. In the present study, the finding that 80 μm reconstructions had a higher diagnostic yield compared with 160 μm scans may relate to canal configuration being a more complex parameter to assess than presence or absence of resorptive defects, or simulated cracks that may be much wider than those seen clinically.

The voxel size did not have an impact on inter-examiner agreement for classification of canal configuration or PAI score (Table 6). This finding suggests the voxel size did not appear to influence inter-examiner variability for these parameters. On the other hand, examiners were significantly less likely to agree regarding image quality for 80 μm scans compared with 125 μm and 160 μm . This most likely relates to greater subjectivity in interpreting image quality when there are more noise and/or artefacts; however, the results should be interpreted with caution due to the small sample size of CBCT images assessed ($N = 27$ scans) and the lack of reference standard. Micro-CT was not used as the reference standard for the CBCT PAI score because in the sectioning process not all the periradicular tissues were removed intact (e.g., sectioning may cut into the lesion). This was necessary to ensure the samples were small to maximize the micro-CT resolution. Increasing the sample sizes would result in an increase in the source-to-object distance, and reduce the spatial resolution obtained. Also, there was no reference standard for interpretation of image quality. As no reference standard existed for image quality, only examiner agreement (and not accuracy) could be assessed. For example, a particular resolution may be associated with higher examiner agreement, but it is possible that both examiners are incorrect in their assessment and therefore that resolution in fact has an inferior performance.

A clear trend was found towards small FOV scans perceived as having a poorer image quality. This primarily appeared to be the case in specimens with metallic restorations, particularly when restorations were located outside the FOV (Figure 3). Images without metallic restorations did not appear to suffer from a decrease in quality. This may relate to partial volume and beam hardening artefacts caused by metallic restorations located near or outside the FOV [43–45]. Additionally, smaller voxel reconstructions have a lower signal-to-noise ratio because the signal received per pixel on the detector is decreased, while the level of noise remains constant [11,46], resulting in noisier images. Despite being perceived as having lower image quality, 80 μm scans demonstrated slightly greater diagnostic accuracy for canal anatomy assessment, suggesting that subjective image quality may not correlate with diagnostic performance [47].

Smaller voxel reconstructions require longer scan times and may therefore be more susceptible to motion artefacts in vivo [48,49]. As this study used static cadaveric specimens, the findings likely represent a best-case imaging scenario. Future studies incorporating simulated patient motion would be valuable.

A limitation of the present study is that voxel size and FOV could not be varied independently because these parameters are intrinsically linked on the CBCT system used. The FOV is decreased as the source-object distance decreases [27,50]. Consequently, the observed differences cannot be attributed solely to voxel size and instead represent the combined imaging protocol associated with each reconstruction setting. In a small number of CBCT machines, the FOV is seemingly held constant despite the voxel size changing. It is likely that in these machines, the large FOV scans are digitally cropped to enable the computer to process the information [11].

The findings should be interpreted within the context of the single CBCT platform evaluated. Different manufacturers employ proprietary detector technologies, image

processing pipelines and reconstruction algorithms, which may influence image quality independently of voxel size. Consequently, the present results should not be assumed to apply directly to other CBCT systems without further validation.

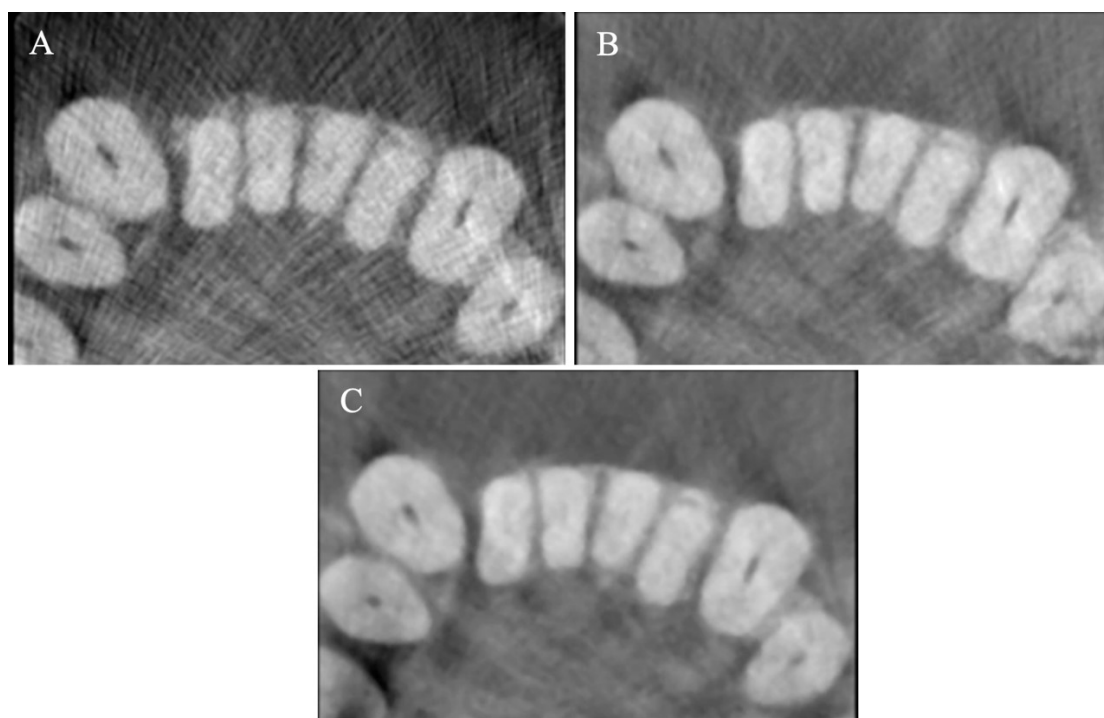


Figure 3. Scans of the same sample taken at (A) 4×4 cm, (B) 6×6 cm, and (C) 8×8 cm. There were metallic restorations present in the posterior teeth, resulting in poorer image quality in the smaller FOV scans due to the partial volume effect.

From a clinical perspective, although $80 \mu\text{m}$ reconstructions demonstrated statistically greater diagnostic accuracy than $160 \mu\text{m}$ reconstructions, the absolute improvement was modest. Consequently, the clinical significance of this difference should be interpreted cautiously and balanced against the increased image noise associated with smaller voxel reconstructions, as well as the higher risk of movement artefacts and radiation optimization principles. Routine acquisition of an additional CBCT scan solely to obtain a smaller voxel reconstruction would not be justified if a diagnostic-quality scan reconstructed at another sub- $200 \mu\text{m}$ voxel size is already available. However, when CBCT is already indicated and assessment of complex canal morphology is particularly important, selecting the smallest available voxel reconstruction may provide a modest diagnostic advantage. In the CBCT system used in this study, this protocol also corresponded to the smallest field of view and therefore the lowest radiation dose. Collimation of the X-ray beam to a limited FOV can reduce the radiation dose by up to 50% [51,52] and reduces irradiation of radiosensitive organs located above and below the dental arches, including the eyes and thyroid [53].

Future advances in artificial intelligence-based image reconstruction and noise reduction algorithms may improve diagnostic performance without requiring progressively smaller voxel sizes or increased radiation exposure. Although grouping all non-Vertucci Type I canal configurations increased the statistical power of the analyses in this study, this approach may have masked differences in diagnostic accuracy among individual complex canal configurations, as demonstrated by the descriptive findings in Table 2. Future multicenter studies incorporating larger numbers of teeth exhibiting complex canal anatomies would allow statistically meaningful comparisons between individual Vertucci canal configurations.

5. Conclusions

CBCT scans reconstructed at 80 μm , 125 μm , and 160 μm showed high accuracy for Vertucci Type I configurations but substantially lower accuracy for more complex canal morphologies such as bifurcating or merging canals and lateral canals. Furthermore, although lateral canals and apical deltas were present in 55% of roots on micro-CT, they were detected in only two roots on CBCT, highlighting an important limitation of current CBCT technology for identifying fine anatomical details. Although 80 μm reconstructions demonstrated slightly greater diagnostic accuracy than 160 μm scans, the absolute improvement was modest. These findings suggest that canal anatomical complexity may have a greater influence on diagnostic performance than differences among currently available sub-200 μm voxel reconstructions. When high-resolution assessment is clinically justified, smaller voxel reconstructions may provide incremental benefit; however, clinicians should remain cautious when interpreting complex canal anatomy regardless of voxel size. Future studies incorporating larger numbers of teeth with complex canal morphologies and simulated patient movement would allow more detailed analyses of specific canal configurations while improving clinical generalizability.

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Abbreviations

The following abbreviations are used in this manuscript:

CBCT Cone-beam computed tomography
PAI Periapical Index

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