Cone-beam Computed Tomographic–based Assessment of Filled C-shaped Canals: Artifact Expression of Cone-beam Computed Tomography as Opposed to Micro–computed Tomography and Nano–computed Tomography

Jardel Francisco Mazzi-Chaves, DDS, MSc, PhD,^{*†} Karla de Faria Vasconcelos, DDS, MSc, PhD,[†] Ruben Pauwels, DDS, MSc, PhD,^{†‡§} Reinhilde Jacobs, DDS, MSc, PhD, Dr Hc,^{†||} and Manoel Damião Sousa-Neto, DDS, MSc, PhD^{*}

SIGNIFICANCE

CBCT imaging has been used as a diagnostic imaging modality for root canal treatment. However, because of large differences in artifact expression between CBCT units, the high-resolution protocols should not be performed in endodontically filled teeth because artifacts may increase.

From the *Department of Restorative Dentistry, School of Dentistry of Ribeirão Preto, University of São Paulo, Ribeirão Preto, São Paulo, Brazil; †Oral and Maxillofacial Surgery, Imaging and Pathology Research Group, Faculty of Medicine, Department of Imaging and Pathology, University of Leuven, University Hospitals Leuven, Leuven, Belgium; ‡Aarhus Institute of Advanced Studies, Aarhus University, Aarhus, Denmark; §Faculty of Dentistry, Department of Radiology, Chulalongkorn University, Bangkok, Thailand; and ||Department of Dental Medicine, Karolinska Institutet, Stockholm, Sweden

Address requests for reprints to Prof Manoel Damião Sousa-Neto, Department of Restorative Dentistry, School of Dentistry of Ribeirão Preto, University of São Paulo, Rua Céila de Oliveira Meirelles 350, 14024-070, Ribeirão Preto, SP, Brazil.
E-mail address: sousanet@forp.usp.br
0099-2399/\$ - see front matter

Copyright © 2020 American Association of Endodontists.
<https://doi.org/10.1016/j.joen.2020.07.010>

ABSTRACT

Introduction: The present study investigated the assessment of root canal fillings in a series of cone-beam computed tomographic (CBCT) images obtained from endodontically treated mandibular molars with C-shaped canals. **Methods:** Clinically comparable high (HR) and normal (NR) resolution protocols were selected in 3D Accuitomo 170 (J Morita Corporation, Kyoto, Japan), NewTom VGi evo (Cefla QR Verona, Verona, Italy), ProMax 3D Max (Pro; Planmeca, Helsinki, Finland), and Pax-i3D Green Premium (Pax; Vatech, Gyeonggi, South Korea). Micro–computed tomographic and nano–computed tomographic images were considered as the reference standard. The set of images was evaluated according to beam hardening artifact patterns (dark streaks, hypodense areas, and volume distortion).

Results: Regarding dark streaks, the Fleiss kappa test showed that Pax HR and NR and Pro HR images showed the highest artifact expression. Hypodense areas were detected in 100% and 99.1% of the images obtained using Pax HR and NR, respectively. Kappa tests showed highest distortion for images derived from the Pax and Pro CBCT devices. Root canal filling assessment was considered appropriate in 100% of the 3D Accuitomo 170 HR, NewTom VGi evo NR, micro–computed tomographic, and nano–computed tomographic images. **Conclusions:** The present study confirms the large variability in CBCT-derived artifact expression. Highlighting the increased artifact expression for particular CBCT systems, it may be concluded that for diagnosis of endodontically filled molars with C-shaped canals, the choice of CBCT unit and protocol is essential. (*J Endod* 2020;■:1–10.)

KEY WORDS

Artefact; beam hardening; root canal filling; CBCT; nanoCT; microCT

Cone-beam computed tomographic (CBCT) imaging has been increasingly used as a complementary diagnostic imaging modality in the planning and follow-up of root canal treatment^{1–9}. However, the presence of a high atomic number and density materials in the scanned volume may lead to the occurrence of beam hardening and, consequently, the formation of artefacts^{1,4,10–13}. Beam hardening, photon starvation, and scattered radiation are responsible for the nonuniformity of gray levels in the images and, consequently, for the formation of different types of artifacts such as dark streaks, hypodense bands, and volumetric distortion or blooming^{1,4,9–11,14}.

Dark streaks are identified by means of rays and lines that usually start from the hyperdense materials and follow through to the end of the field of view, whereas hypodense areas are characterized by the presence of dark regions adjacent to the high-density material. On the other hand, distortion artifacts lead to overestimation of the volume of high-density materials^{1,4,10,11,14}.

These artifacts may hamper diagnosis based on misleading image information or obscured visualization in relation to the detection of fractures and perforations, anatomic variations such as accessory and lateral canals, overfillings, or the presence of gaps and voids inside the root canal obturation. Failure to obtain the adequate diagnosis may lead to inadequate endodontic treatment or even tooth extraction^{1,4,9,12}.

Therefore, it is important to understand how artifacts generated by root canal fillings are expressed in different CBCT devices. The aim of the present study was to assess artifact expression on CBCT-derived images of filled C-shaped canals as opposed to micro-computed tomographic (micro-CT) devices using nano-computed tomographic (nano-CT) imaging as the reference standard.

MATERIALS AND METHODS

After obtaining local research ethics committee approval (no. 80666517.2.0000.5419, University of São Paulo, Ribeirão Preto, SP, Brazil), 60 first and second mandibular molars freshly extracted for periodontal reasons collected from the tooth biobank (location, university, city, and country) and stored in 0.1% thymol solution were selected. The requirement to obtain informed consent from patients was waived by the ethics committee.

After washing the teeth in running water for 24 hours, we cleaned their outer root surface by ultrasound scraping (Profil II Ceramic; Dabi Atlante Ltda, Ribeirão Preto, SP, Brazil). Subsequently, we examined the teeth macroscopically and radiographed them using the parallel technique (Spectro 70X Eletronica, Dabi Atlante Ltda) in the ortho- and mesioradial directions using a digital sensor (Fona CDRelite; Schick DMM, Bandeirantes, PR, Brazil) to preselect teeth with fully formed roots and canals without calcifications, resorptions, or cracks and without previous endodontic treatment.

Preliminary Micro-CT Scanning

We scanned the specimens using the SKYSCAN 1174 microCT unit (Bruker SkyScan, Kontich, Belgium) at 50 kVp, 800

μA, an isotropic resolution of 19.65 μm, rotation of 360° around the vertical axis with a 1° rotation step, a total of 2 frames, a 0.5-mm aluminum filter, and a scan time of 40 minutes. The 2-dimensional projections were saved in the Tagged Image File format (.tiff). After scanning, we immersed the teeth in saline solution and stored them in an oven (37°C).

For reconstruction, we used NRecon v.1.6.6.0 software (Bruker SkyScan), applying a ring artifact reduction of 10, a beam hardening reduction of 30%, and a smoothing of 2. The image histograms varied from 0.003–0.15 and were saved in the bitmap (.bmp) format. Using DataViewer v.1.5.4.0 (Bruker SkyScan), we carefully evaluated the samples and selected 12 mandibular molars with roots free of pulp calcifications or internal resorption and with C-shaped root canals.

Biomechanical Preparation and Root Canal Filling

The root canals were irrigated with 2 mL 2.5% sodium hypochlorite (Fisher Scientific Company, Ottawa, ON, Canada) with a disposable plastic syringe (Ultradent Products Inc, South Jordan, UT) and a 0.30-mm NaviTip needle (Ultradent Products Inc). Then, the root canals were explored with #10 and #15 K stainless steel files (Dentsply Sirona Endodontics, Charlotte, NC) until the tip coincided with the apical foramen, reaching the real tooth length. From this measurement, 0.5 mm was subtracted to establish the working length.

The biomechanical preparation was performed with a Reciproc Blue R25 (25.08) reciprocating file (VDW GmbH, Munich, Germany) coupled to the X-Smart Plus (Dentsply Maillefer, Ballaigues, Switzerland). Canals were prepared in accordance with the manufacturer's instructions using a pecking motion with the file from the canal being removed every 3 advances for cleaning with gauze until reaching the working length.

Irrigation was performed with 2.5% sodium hypochlorite, aspirating and flooding the canals at each pecking motion, with a disposable plastic syringe and NaviTip needle. After instrumentation, the final irrigation with 2 mL EDTA (Sigma Aldrich BVBA, Overijse, Belgium) was performed. Initially, the root canals were dried with a Capillary Tip aspiration cannula (Ultradent Products Inc) and then using R25 (VDW GmbH) absorbent paper points.

For obturation, we manipulated AH Plus sealer (Dentsply De Trey, Konstanz, Germany) according to the manufacturer's instructions and inserted it into the root canal using a #30 K

hand file (Dentsply Sirona Endodontics) with a counterclockwise rotary motion. We covered the main gutta-percha cone (R25) with sealer and gradually introduced it up to the working length using circular movements.

Subsequently, we inserted fine-medium accessory cones (Dentsply Maillefer) into the root canals and thermoplasticized them with a McSpadden #30 condenser (Dentsply Maillefer) traversed up to the middle third of the root canal at low rotation. Afterward, we performed vertical condensation using a Paiva no. 2 condenser (Duflex; SS White, Lakewood, NJ) with light and firm pressure in the apical direction for 5 seconds. For final cleaning of the root canal entrance, we used a sponge moistened with alcohol and sealed the specimens with a temporary sealer. Then, we stored the specimens individually in numbered Eppendorf tubes at 37°C and 100% humidity where they remained in these conditions for a period of 3 times the length of the sealer setting time as recommended by the manufacturer (24 hours).

Nano-CT, Micro-CT, and CBCT Image Acquisition

Table 1 shows the acquisition parameters for nano-CT, micro-CT, and CBCT imaging.

Nano-CT Imaging

After root canal obturation, we fixed the specimens with paraffin wax film (Parafilm M; Bemis Company Inc, Neenah, WI) and scanned them using the Phoenix NanoTom M Nano-computed tomographic system (GE, Wunstorf, Germany).

Micro-CT Imaging

Using the same fixation method, we scanned the specimens with the SkyScan 1172 (Bruker SkyScan). After acquiring micro-CT and nano-CT scans, we performed reconstruction using NRecon v1.6.6.0 software and saved the images in the joint bitmap (.bmp) format.

Table 2 describes the reconstruction parameters.

CBCT Imaging

To simulate attenuation of the X-ray beams in soft and hard tissues, we fixed the samples in a macerated human jaw coated with a 2-mm layer of Mix-D (KU Leuven, Leuven, Belgium)¹⁵. Then, specimens were scanned using the following CBCT machines: 3D Accuitomo 170 (Acc; J Morita Corporation, Kyoto, Japan), NewTom VGi evo (NT; Cefla QR Verona, Verona, Italy), Planmeca ProMax 3D Max (Pro; Planmeca, Helsinki, Finland), and Pax-3 Green

TABLE 1 - The Scanning Protocols Used to Acquire Nano-computed Tomographic, Micro-computed Tomographic, and Cone-beam Computed Tomographic Images

	NanoCT	MicroCT	3D Accuitomo 170	NewTom VGi evo	ProMax 3D Max	Pax-i3D Green Premium
Field of view	—	—	4 × 4 cm	5 × 5 cm	5 × 5 cm	8 × 8 cm
Current	100 mA	100 mA	5 mA	3 mA	12 mA	6 mA
Voltage	100 kVp	100 kVp	90 kVp	110 kVp	96 kVp	108 kVp
Isotropic voxel	0.004 mm	0.013 mm	0.08 mm	0.10 mm	0.075 mm	0.12 mm
Exposure time	11700 s	9000 s	30.8 s	12 s	15 s	11 s
Filter	Cu 0.1 mm	CuAl	Al	Al	Al	Al
Rotation	360°	360°	4.2 mm	9.3 mm	20 mm	2.5 mm
2-Dimensional projections	2401	516	360°	360°	270°	360°
Dose-area product	—	—	924	335	774	667
Millampere time product	—	—	7.06 mGy·cm ²	1.48 mGy·cm ²	11.54 mGy·cm ²	5.69 mGy·cm ²
Protocol	HR	HR	154 mA	36 mA	180 mA	66 mA
			NR	HR	NR	HR
				NR	NR	NR
						2.11 mGy·cm ²
						44 mA
						NR

HR, high resolution; NR, normal resolution.

Premium (Pax; Vatech, Gyeonggi, South Korea). We standardized the acquisition parameters by using 2 scanning protocols: high resolution (HR) and normal resolution (NR) (Table 1).

Nano-CT, Micro-CT, and CBCT Image Registration

Before registration, we performed several processing steps using ImageJ software (National Institutes of Health, Bethesda, MD)¹⁶. Custom macros automated the procedure, except for manual selection of the region of interest (ROI) containing the tooth. For nano-CT and micro-CT scans, we cropped the image stack to the ROI within the selected image, calibrated the stack according to a voxel size of 4 μ m for nano-CT and 13.059 μ m for micro-CT images, and saved the stack as a single-file Digital Imaging and Communications in Medicine (DICOM) image.

For the CBCT scans, the macro adjusted the image rotation to the nearest 90° corresponding to the nano-CT and micro-CT scans of this sample. Afterward, the image stack was cropped to the ROI in the axial plane. Then, the operator also determined the first and last slice containing the tooth, thus only retaining slices containing the tooth to avoid excessive memory consumption during registration. Resampling of the scan was performed to a voxel size of 13.059 μ m using bilinear interpolation, and then the resulting stack was saved as a single-file DICOM image.

Afterward, we registered the images using Elastix software (<http://elastix.isi.uu.nl/>; University Medical Centre Utrecht and collaborators, Utrecht, Netherlands)¹⁷, which is partially based on the Insight Segmentation and Registration Toolkit (ITK, Kitware Inc, Clifton Park, NY). We performed multiresolution registration based on the mutual information metric, with the nano-CT and micro-CT scan as the “fixed” image and the CBCT scan as the “moving” image. The registered image transformation was rigid, implying that only image translation and rotation was possible (no scaling or other deformations). Aligned CBCT images were saved in the DICOM format.

Qualitative Evaluation of Nano-CT, Micro-CT and CBCT Images

For the evaluation, 36 axial, sagittal, and coronal reconstructions of all image modalities were selected for each scan protocol, totaling 360 images. Afterward, the slices were grouped into axial, sagittal, and coronal and randomly arranged on different PowerPoint slides (Microsoft, Redmond, WA). A

TABLE 2 - The Reconstruction Protocols Used for Nano-computed (Nano-CT) and Micro-computed Tomographic (Micro-CT) Images

Reconstruction settings	NanoCT	MicroCT
Ring artifact reduction	3	5
Beam hardening reduction (%)	30	50
Smoothing	3	4
Attenuation histogram	0.004–0.07	

randomized image sequence of each sample was generated.

Three observers were included, 2 endodontists and 1 dentomaxillofacial radiologist with experience in nano-CT, micro-CT, and CBCT image analysis. A qualitative evaluation was performed of the artifact expression (dark streaks, hypodense areas, and distortion) as described further later. During training and calibration, observers received the definition and examples of each parameter to be evaluated and instructions about the scores to be assigned to each parameter (Fig. 1). We used 2 Barco Eonis 22-inch monitors (Barco NV Company Research, Kortrijk, Belgium) with a screen resolution of 1920 × 1080 pixels.

Observers performed qualitative analysis independently in 2 sessions, with a 15-day interval between analyses, in a dimmed and noise-free room to evaluate the intra- and interobserver agreement. Throughout all evaluation sessions, examiners were given images of the criteria and scores to be evaluated (Fig. 1).

The artifacts evaluated were dark streaks, hypodense areas, and volume distortion of the root filling material. The observers classified the artifact types generated relative to their presence in all images using the following scores: 1, artifact definitely absent; 2, artifact probably absent; 3, unsure; 4, artifact probably present; and 5, artifact definitely present (Fig. 1).

Observers also judged the images with regard to their quality for use in endodontic diagnosis, considering the possibility of observing fractures, cracks, perforations, internal and external resorptions, unsealed areas inside the root canals, the presence of fractured instruments, and over- or underfilling. Furthermore, the observers were instructed to answer the following question: “How confident are you about your response?” grading the confidence level of their own response. Values ranged from 0–5, where 0 was not confident and 5 was extremely confident (Fig. 1).

Subjective evaluation parameters

Dark Streaks		Hypodense Areas		Distortion	
1 – Definitely absent 2 – Probably absent 3 – Unsure 4 – Probably present 5 – Definitely present		1 – Definitely absent 2 – Probably absent 3 – Unsure 4 – Probably present 5 – Definitely present		1 – Definitely absent 2 – Probably absent 3 – Unsure 4 – Probably present 5 – Definitely present	
Absent	Present	Absent	Present	Absent	Present

Can this image be still useful for endodontic diagnosis?

Yes No

0 – No
1 – Yes

How confident are you about your answer?

0 1 2 3 4 5

Not at all confident Extremely confident

FIGURE 1 – Parameters and respective scores defined for subjective evaluation with examples representing the types of beam hardening artifacts generated by high-density materials within the root canal system.

Statistical Analysis

A statistician calculated the Fleiss kappa values for every variable separately and compared them between machines for every combination of parameter and view by means of a 1000-fold nonparametric bootstrap.

The occurrence of artifacts was evaluated by taking into consideration all the

relevant class of occurrence groupings (definitely absent <-> probably absent or worse, definitely or probably absent <-> unsure or worse, definitely or probably absent or unsure <-> probably present or worse, and definitely or probably absent or unsure or probably present <-> definitely present). For every grouping, a generalized linear mixed

model was constructed for binary responses with a logit link, with the observer as the random factor and the machine and view as the crossed fixed factors. Machines were compared for every view separately, and a correction was made for the simultaneous hypothesis according to Šidák¹⁸. In addition, comparisons were made with the best scan

FIGURE 2 – Axial slices obtained for the evaluation of artifacts. Dark streaks and hypodense areas are identified by red and yellow arrows, respectively. Acquisition protocols are represented by (A) nano-CT imaging, (B) micro-CT imaging, (C) Acc HR, (D) Acc NR, (E) NT HR, (F) NT NR, (G) Pro HR, (H) Pro NR, (I) Pax HR, and (J) Pax NR. It is possible to observe a higher expression of dark streaks in the G, I, and J protocols and a lower expression in the A–F protocols. For the hypodense areas, a higher expression can be observed in protocols I and J compared with protocols A, B, and F.

TABLE 3 - Comparison among the Different Scanning Protocols for the Presence of Dark Streaks and Hypodense Areas Present in Axial, Sagittal, and Coronal Slices

Protocols	Definitely absent	Probably absent	Unsure	Probably present
	Does not differ from the best (95%): indicated by X			
	Dark Streaks			
NanoCT Phoenix NanoTom M	X	X	X	X
MicroCT 1173	X	X	X	X
3D Accuitomo 170 HR	X	X	X	X
3D Accuitomo 170 NR	X	X	X	X
NewTom VGi evo HR	X	X	X	X
NewTom VGi evo NR	X	X	X	X
ProMax 3D Max HR				X
ProMax 3D Max NR			X	X
Pax-i3D Green Premium HR				
Pax-i3D Green Premium NR				
Protocols	Hypodense areas			
	Definitely absent	Probably absent	Unsure	Probably present
	Does not differ from the best (95%): indicated by X			
NanoCT Phoenix NanoTom M	X	X	X	X
MicroCT 1173	X	X	X	X
3D Accuitomo 170 HR				
3D Accuitomo 170 NR				
NewTom VGi evo HR				X
NewTom VGi evo NR				X
ProMax 3D Max HR				
ProMax 3D Max NR				
Pax-i3D Green Premium HR				
Pax-i3D Green Premium NR				
Protocols	Distortion			
	Definitely absent	Probably absent	Unsure	Probably present
	Does not differ from the best (95%): indicated by X			
NanoCT Phoenix NanoTom M	X	X	X	X
MicroCT 1173	X	X	X	X
3D Accuitomo 170 HR				
3D Accuitomo 170 NR				
NewTom VGi evo HR				
NewTom VGi evo NR				
ProMax 3D Max HR				
ProMax 3D Max NR				
Pax-i3D Green Premium HR				
Pax-i3D Green Premium NR				

HR, high-resolution protocol; NR, standard resolution protocol.

protocol at a significance level of .05 for every view separately. All statistical tests were performed with SAS 9.1 software (SAS, Cary, NC), with the significance level fixed at .05.

RESULTS

The Fleiss kappa test results for inter- and intraobserver agreement according to the artifacts (dark streaks, hypodense areas, and distortion), protocols (HR and NR), and reconstructions (axial, sagittal, and coronal) were 0.56 and 0.67, respectively.

Regarding dark streaks, we observed a higher artifact expression percentage in axial slices followed by coronal and sagittal

slices. Furthermore, we observed a prevalence, irrespective of the slice assessed, as follows: for Pax NR, 38%; for Pax HR, 34.3%; and for Pro HR, 3.7%. For the protocols of both Acc and NT, we observed a significantly lower artifact expression ($P < .05$) (Fig. 2A–J).

Regarding hypodense areas, we were able to observe that the presence did not differ statistically from that of the nano-CT reference standard ($P < .05$) for the NT (HR and NR) CBCT protocols (Table 3). On the other hand, Pro HR, Pax HR, and Pax NR differed from nano-CT imaging ($P < .05$). There was a higher expression of the presence of this artifact in percentage in the axial slices followed by

sagittal and coronal slices with a higher prevalence, irrespective of the reconstruction, as follows: for Pax NR, 100%; for Pax HR, 99.1%; for Pro HR, 31.5%; for Acc HR, 26.9%; for Pro NR, 18.5%; and for Acc NR, 17.6%. We observed the lowest occurrence for the NT NR (3.7%) and NT HR (2.8%) protocols ($P < .05$). Figure 2 shows a higher value of expression of hypodense areas in the sagittal and coronal slices for all scanning protocols performed in the Pro and Pax CBCT machines.

When evaluating the filling's distortion, we were able to observe that only micro-CT imaging did not differ statistically from the nano-CT reference standard ($P > .05$) (Table 3). Regarding the protocols, regardless of the slice evaluated, the incidence was as follows: for Pax HR and Pro NR, 100%; for Pax NR and Pro HR, 99.1%; for NT NR, 52.8%; for Acc NR, 42.6%; for NT HR, 32.4%; and for Acc HR, 26.9% ($P < .05$) (Fig. 3A–J).

Figure 3 shows higher volumetric distortion values of the root canal filling material for all the protocols performed in the Pro and Pax CBCT machines irrespective of the slices evaluated. This artifact may mimic excessive overinstrumentation and wear of the root canal walls during biomechanical preparation.

Relative to the possibility of endodontic diagnosis, in 100% of the images obtained in the nano-CT, micro-CT, Acc HR, and NT HR protocols and in 97.2% and 91.7% of the images acquired in Acc NR and NT NR, respectively, it would be possible to use images for endodontics diagnosis irrespective of the axial, sagittal, and coronal reconstructions evaluated ($P < .05$) (Table 4 and Fig. 4A–F).

On the other hand, it was judged that endodontic diagnosis was impaired for 100% of the images obtained with the Pro NR and Pax HR protocols and in 71.3% and 98.1% of Pro HR and Pax NR, respectively, irrespective of the slices evaluated ($P < .05$) (Table 4 and Fig. 5A–D).

When we evaluated the confidence level of the observers' answers regarding the possibility of using the images for endodontic diagnosis, it was found that the observers were significantly more confident of their answers for nano-CT imaging (100%), Pax HR and NR (99.1%), Pro NR (98.1%), micro-CT imaging (87%), and Pro HR (62%) ($P < .05$) (Table 4). Acc and NT CBCT machines had the lowest confidence scores.

DISCUSSION

In our study, we observed a higher level of expression of artifacts in axial reconstructions

FIGURE 3 – Axial slices obtained for the evaluation of artifacts. Volumetric distortion or blooming are indicated by *dotted lines* that show the actual outline of the filling material. Acquisition protocols are represented by (A) nano-CT images, (B) micro-CT images, (C) Acc HR, (D) Acc NR, (E) NT HR, (F) NT NR, (G) Pro HR, (H) Pro NR, (I) Pax HR, and (J) Pax NR. *Red dotted lines* indicate the reference standard protocol, which is considered minimal or no distortion volume of filling material. The *green dotted lines* evidence distortion present in the filling material protocols G–J compared with protocols A and B. For protocol C–F (*dotted blue lines*), it is possible to identify the presence of distortion, although it is not statistically different from the reference protocol.

irrespective of the protocol or equipment used. According to several studies^{19–21}, the streak artifacts are more prominent in axial reconstructions, which corresponds to the X-ray beam projection plane.

The lower generation of dark streaks, hypodense areas, and distortion found for the Acc and NT was because of the association between factors such as the higher number of projections acquired, mainly in the HR protocol, and was related to some artifact suppression reconstruction algorithm. Moreover, particularly for the acquisitions made using the NT, the high kVp may also have had an influence. These results corroborated findings in the literature that have demonstrated that the use of high kVp is

associated with the production of more projection images, providing more information for the reconstruction process and thus improving overall image quality, which can reduce the expression of metal artifacts^{1,3,4,6,7,10,11,14,19,20,22–26}. However, it is worth emphasizing that the higher the number of projections, the longer the time of scanning, processing, and reconstruction, which could lead to the necessity of new acquisition because of motion artefacts^{6,12,19,20,25–27}.

A high kVp increases the average and maximum energy of the X-ray beam, leading to greater penetration capacity and reducing the beam hardening effect^{6,7,19,20,24–26,28–31}. However, it is worth mentioning that an

increase in kVp or mA directly influences the amount of radiation dose to which the patient was exposed^{19,20,24,29,30}. Therefore, a higher kV must be balanced with a reduction in mA, taking all effects on image quality into account.

In the results, we observed the worst performance with regard to generating metallic artifacts in the images acquired from the Pro and Pax protocol machines as shown in [Tables 3 and 4](#). The greater expression of dark streaks, hypodense areas, and distortion for the Pro could be explained by its lower kVp and a reduced number of projections because of a 270° rotation^{4,32–35}. For the Pax, the kVp was relatively high for the HR protocol, but this does not result in a statistical improvement versus the low kV NR protocol. Furthermore, this unit has a unique scan geometry involving a narrow vertical detector and several rotations, making it difficult to compare or explain results based on technical specifications. Reconstruction-specific factors, such as pre- and postprocessing, filtering, and histogram allocation, are presumed to play a major role in artifact expression as well, although the exact cause of different artifact expression cannot be determined because of the proprietary nature of reconstruction algorithm. For this reason, it cannot be expected that “endo” scanning protocols and metal artifact reduction modes improve the diagnostic image quality in the presence of endodontic restorations. For metal artifact reduction algorithms currently implemented in clinical CBCT imaging, several

TABLE 4 - Comparison among the Different Scanning Protocols for the Possibility of Using Images for Diagnostic Purposes in Endodontics

Protocols	Does not differ from the best ($\alpha = 0.05$): indicated by X	
	Useful images for endodontic diagnosis	
NanoCT Phoenix NanoTom M	X	
MicroCT SKYSCAN 1173	X	
3D Accuitomo 170 HR	X	
3D Accuitomo 170 NR	X	
NewTom VGi evo HR	X	
NewTom VGi evo NR	X	
ProMax 3D Max HR		
ProMax 3D Max NR		
Pax-i3D Green Premium HR		
Pax-i3D Green Premium NR		

HR, high-resolution protocol; NR, standard resolution protocol.

FIGURE 4 – Axial, sagittal, and coronal slices evaluated regarding the possibility of using CBCT images for endodontic diagnosis purposes. Acquisition protocols are represented by (A) nano-CT imaging, (B) micro-CT imaging, (C) Acc HR, (D) Acc NR, (E) NT HR, and (F) NT NR. Images from A–F protocols show the diagnostic potential for assessing endodontic treatment considering lower expressions of artifacts.

studies have shown little or no improvement in diagnostic efficacy^{5–7,9}. Further studies are needed to explore the expression of endodontic artifacts and the different influencing factors at a fundamental level. Another important factor is the detector efficiency and sensitivity; although scintillator-based flat-panel detectors are ubiquitous in CBCT imaging, the performance of detectors from different CBCT units may vary. This is particularly relevant for metal artifacts because of photon starvation because this is partially determined by the minimally detectable signal of the detector system^{6,7,10}.

Images acquired with micro-CT and nano-CT (reference standard) scanning showed the absence or reduction of artifact formation compared with the CBCT protocols. These results could be explained by the high detector sensitivity and the large number of projection images acquired. Moreover, the acquisition of images of only the tooth, without the jaw and Mix-D in the field of view, reduced beam hardening, photon starvation, and X-ray scattering^{6,7,10,29,36}.

Finally, another point that contributed to the reduction in the expression of artifacts in

nano-CT and micro-CT imaging was the software used in the image reconstruction, which, unlike the CBCT software evaluated in the present study, allowed the use of tools for the reduction of metallic artifacts such as beam hardening correction³⁶. These tools allowed the operator to control the beam hardening phenomenon by means of a linearization method with second-order polynomial adjustment algorithms after acquisition of the volumes, unlike the CBCT software in which the reconstruction process is automatic and the extent and type of beam hardening correction is proprietary information^{9,25,26,37}.

On clinical scans, dark streaks can simulate and/or mimic the presence of root fractures and anatomic variations such as an isthmus and lateral, accessory, and secondary canals. The hypodense areas may interfere with the diagnosis of voids and/or filling quality and internal and external resorption and, in cases of failure, suggesting the need for endodontic retreatment and/or tooth extraction and volumetric distortion, may suggest over- or underfilling and excessive wear of the root canal walls. Moreover, such artifacts may mimic the presence of fractured

instruments within the root canals and anatomic structures of interest^{1,4,6,7,9–11,24–26,36–38}.

CONCLUSIONS

Because of large differences in artifact expression between CBCT units, the fine-tuning of image acquisition parameters for the minimization of artifact expression should be performed for individual machines and specific applications. When acquiring a CBCT unit for primarily endodontic use, the choice of the CBCT unit and protocol is essential. In CBCT machines with an inherent lower image quality, protocols boosting the resolution should not be recommended to visualize endodontically treated teeth because artifacts may increase.

ACKNOWLEDGMENTS

We thank Wim Coucke, a freelance statistician, for performing the statistics of this study, and the observers Karla de Faria Vasconcelos, Ana Ramos, and Bernardo Camargo for making it possible to obtain the clinical results of this study.

FIGURE 5 – Axial, sagittal, and coronal reconstructions evaluated regarding the possibility of using CBCT images for endodontic diagnosis purposes. The images from the *A–D* protocols show poor diagnostic potential diagnosis to assess endodontic treatment because of a higher expression of beam hardening artifacts. (*A*) Pro HR, (*B*) Pro NR, (*C*) Pax HR, and (*D*) Pax NR.

Supported by the Coordination for the Improvement of Higher Education Personnel (CAPES-Brazil Process no.

33002029032P4), the European Union Horizon 2020 Research and Innovation Programme under the Marie Skłodowska-

Curie grant agreement number 754513 (R.P.), and Aarhus University Research Foundation (AIAS-COFUND).

REFERENCES

1. Vasconcelos KF, Nicolielo LF, Nascimento MC, et al. Artefact expression associated with several cone-beam computed tomographic machines when imaging root filled teeth. *Int Endod J* 2015;48:994–1000.
2. Patel S. Response to the letter entitled: "Cone beam computed tomography in Endodontics". *Int Endod J* 2016;49:313.
3. Celikten B, Jacobs R, De Faria Vasconcelos K, et al. Assessment of volumetric distortion artifact in filled root canals using different cone-beam computed tomographic devices. *J Endod* 2017;43:1517–21.
4. Codari M, De Faria Vasconcelos K, Ferreira Pinheiro Nicolielo L, et al. Quantitative evaluation of metal artifacts using different CBCT devices, high-density materials and field of views. *Clin Oral Implants Res* 2017;28:1509–14.

5. Queiroz PM, Rovaris K, Gaêta-Araujo H, et al. Influence of artifact reduction tools in micro-computed tomography images for endodontic research. *J Endod* 2017;43:2108–11.
6. Fox A, Basrani B, Kishen A, Lam EW. A novel method for characterizing beam hardening artifacts in cone-beam computed tomographic images. *J Endod* 2018;44:869–74.
7. Fox A, Basrani B, Lam EW. The performance of a zirconium-based root filling material with artifact reduction properties in the detection of artificially induced root fractures using cone-beam computed tomographic imaging. *J Endod* 2018;44:828–33.
8. Freitas DQ, Fontenele RC, Nascimento EH, et al. Influence of acquisition parameters on the magnitude of cone beam computed tomography artifacts. *Dentomaxillofac Radiol* 2018;47:20180151.
9. Vasconcelos KD, Codari M, Queiroz PM, et al. The performance of metal artifact reduction algorithms in cone beam computed tomography images considering the effects of materials, metal positions, and fields of view. *Oral Surg Oral Med Oral Pathol Oral Radiol* 2018;127:71–6.
10. Schulze R, Heil U, Gross D, et al. Artefacts in CBCT: a review. *Dentomaxillofac Radiol* 2011;40:265–73.
11. Pauwels R, Stamatakis H, Bosmans H, et al. Quantification of metal artifacts on cone beam computed tomography images. *Clin Oral Implants Res* 2013;24(Suppl A100):94–9.
12. Huang Y, Celikten B, de Faria Vasconcelos K, et al. Micro-CT and nano-CT analysis of filling quality of three different endodontic sealers. *Dentomaxillofac Radiol* 2017;46:20170223.
13. Nagarajappa A, Dwivedi N, Tiwari R. Artifacts: the downturn of CBCT image. *J Int Soc Prev Community Dent* 2015;5:440–5.
14. Decurcio DA, Bueno MR, De Alencar AH, et al. Effect of root canal filling materials on dimensions of cone-beam computed tomography images. *J Appl Oral Sci* 2012;20:260–7.
15. Oenning AC, Salmon B, Vasconcelos KF, et al. DIMITRA paediatric skull phantoms: development of age-specific paediatric models for dentomaxillofacial radiology research. *Dentomaxillofac Radiol* 2018;47:20170285.
16. Schindelin J, Arganda-Carreras I, Frise E, et al. Fiji: an open-source platform for biological-image analysis. *Nat Methods* 2012;9:676–82.
17. Klein S, Staring M, Murphy K, et al. Elastix: a toolbox for intensity-based medical image registration. *IEEE Trans Med Imaging* 2010;29:196–205.
18. Šidák ZK. Rectangular confidence regions for the means of multivariate normal distributions. *J Am Stat Assoc* 1967;62:626–33.
19. Bechara B, Alex McMahan C, Moore W, et al. Cone beam CT scans with and without artefact reduction in root fracture detection of endodontically treated teeth. *Dentomaxillofac Radiol* 2013a;42:20120245.
20. Bechara B, McMahan CA, Nasseh I, et al. Number of basis images effect on detection of root fractures in endodontically treated teeth using a cone beam computed tomography machine: an in vitro study. *Oral Surg Oral Med Oral Pathol Oral Radiol* 2013;115:676–81.
21. Wanderley VA, Freitas DQ, Haiteir-Neto F, Oliveira ML. Influence of tooth orientation on the detection of vertical root fracture in cone-beam computed tomography. *J Endod* 2018;44:1168–72.
22. Patel S, Dawood A, Ford TP, Whaites E. The potential applications of cone beam computed tomography in the management of endodontic problems. *Int Endod J* 2007a;40:818–30.
23. Patel V, More A, Hoffmann K, et al. Region-of-interest (ROI) cone-beam computed tomography (CBCT) using rotational digital subtraction angiography (DSA) acquisition. *Med Phys* 2007b;34:2343.
24. Nemtoi A, Czink C, Haba D, Gahleitner A. Cone beam CT: a current overview of devices. *Dentomaxillofac Radiol* 2013;42:20120443.
25. Queiroz PM, Santaella GM, Capelozza AL, et al. Zoom reconstruction tool: evaluation of image quality and influence on the diagnosis of root fracture. *J Endod* 2018;44:621–5.
26. Queiroz PM, Santaella GM, Groppo FC, Freitas DQ. Metal artifact production and reduction in CBCT with different numbers of basis images. *Imaging Sci Dent* 2018;48:41.
27. Spin-Neto R, Gotfredsen E, Wenzel A. Impact of voxel size variation on CBCT-based diagnostic outcome in dentistry: a systematic review. *J Digit Imaging* 2013;26:813–20.

28. Patel S, Durack C, Abella F, et al. European Society of Endodontology, European Society of Endodontology position statement: the use of CBCT in endodontics. *Int Endod J* 2014;47:502–4.
29. Pauwels R, Araki K, Siewerdsen JH, Thongvigitmanee SS. Technical aspects of dental CBCT: state of the art. *Dentomaxillofac Radiol* 2015;44:20140224.
30. Pauwels R, Seynaeve L, Henriques JC, et al. Optimization of dental CBCT exposures through mAs reduction. *Dentomaxillofac Radiol* 2015;44:20150108.
31. Pauwels R, Jacobs R, Bogaerts R, et al. Reduction of scatter-induced image noise in cone beam computed tomography: effect of field of view size and position. *Oral Surg Oral Med Oral Pathol Oral Radiol* 2016;121:188–95.
32. Esmaeili F, Johari M, Haddadi P, Vatankhah M. Beam hardening artifacts: comparison between two cone beam computed tomography scanners. *J Dent Res Dent Clin Dent Prospects* 2012;6:49–53.
33. Hunter A, McDavid W. Characterization and correction of cupping effect artefacts in cone beam CT. *Dentomaxillofac Radiol* 2012;41:217–23.
34. Kocasarac HD, Helvacioğlu Yigit D, Bechara B, et al. Contrast-to-noise ratio with different settings in a CBCT machine in presence of different root-end filling materials: an in vitro study. *Dentomaxillofac Radiol* 2016;45:20160012.
35. Brasil DM, Pauwels R, Coucke W, et al. Image quality optimization using a narrow vertical detector dental cone-beam CT. *Dentomaxillofac Radiol* 2019;48:20180357.
36. Celikten B, Uzuntas CF, Orhan AI, et al. Evaluation of root canal sealer filling quality using a single-cone technique in oval shaped canals: an in vitro micro-CT study. *Scanning* 2016;38:133–40.
37. Gaêta-Araujo H, Silva De Souza GQ, Freitas DQ, De Oliveira-Santos C. Optimization of tube current in cone-beam computed tomography for the detection of vertical root fractures with different intracanal materials. *J Endod* 2017;43:1668–73.
38. Helvacioğlu-Yigit D, Demirtürk Kocasarac H, Bechara B, Noujeim M. Evaluation and reduction of artifacts generated by 4 different root-end filling materials by using multiple cone-beam computed tomography imaging settings. *J Endod* 2016;42:307–14.