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Impact of Voxel Size Variation on CBCT-Based Diagnostic Outcome in Dentistry: a Systematic Review

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Abstract The objective of this study was to make a systematic review on the impact of voxel size in cone beam computed tomography (CBCT)-based image acquisition, retrieving evidence regarding the diagnostic outcome of those images. The MEDLINE bibliographic database was searched from 1950 to June 2012 for reports comparing diverse CBCT voxel sizes. The search strategy was limited to English-language publications using the following combined terms in the search strategy: (voxel or FOV or field of view or resolution) and (CBCT or cone beam CT). The results from the review identified 20 publications that qualitatively or quantitatively assessed the influence of voxel size on CBCT-based diagnostic outcome, and in which the methodology/results comprised at least one of the expected parameters (image acquisition, reconstruction protocols, type of diagnostic task, and presence of a gold standard). The diagnostic task assessed in the studies was diverse, including the detection of root fractures, the detection of caries lesions, and accuracy of 3D surface reconstruction and of bony measurements, among others. From the studies assessed, it is clear that no general protocol can be yet defined for CBCT examination of specific diagnostic tasks in dentistry. Rationale in this direction is an important step to define the utility of CBCT imaging.

Keywords Dentistry · Cone beam CT · Voxel size · Diagnostic outcome · Image quality

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Introduction

Cone beam computed tomography (CBCT) is a relatively new imaging technology that provides multi-planar images in submillimeter resolution [1]. In the last years, CBCT has achieved wide acceptance in dentomaxillofacial imaging and has fundamentally replaced conventional tomography for several diagnostic tasks in dentistry [2, 3]. The main advantage of CBCT is its lower acquisition time and patient dose when compared to medical CT scanning [3–6].

In clinical practice, the image quality of CBCT scans and the ability of CBCT to display anatomic features and pathology is influenced by a number of variables such as the scanning unit, the field of view (FOV), examined object, examination time, tube voltage and amperage, and also spatial resolution defined by the voxel size [7]. The size of a voxel is defined by its height, width, and depth, and CBCT voxels are generally isotropic (the three parameters are equal) [8]. The voxel size of a 3D image is equivalent to the pixel resolution in 2D images, and, in this case, a resolution of 300 ppi (pixels per inch) would directly correlate to a voxel size of 0.085 mm. Images acquired in smaller voxel sizes, although "prettier" and sharper from a subjective point of view[9], will increase the radiation dose to the patient but might provide the same diagnostic outcome as lower resolution images [10]. Thus, it is important to ponder that the comparison of CBCT examinations with various voxel settings is relevant to understand the impact of the inherent image quality on the reliability and accuracy of the diagnostic outcome [11].

For medical CT examinations, settings or protocols for any application are commonly discussed in the literature [8, 12, 13]. In opposition to that, rationales for protocols and their impact on CBCT-based diagnosis are not yet available in dentistry. In an attempt to search for a rationale concerning protocols for settings in CBCT imaging, our objective was to perform a systematic review on the impact of voxel size variation on CBCT-based image acquisition, retrieving evidence regarding the diagnostic outcome of those images.

Material and Methods

The MEDLINE (PubMed) bibliographic database was searched from 1950 to May 2012 for reports comparing diverse CBCT voxel sizes. The search strategy was limited to English-language publications using the following combined terms in the search strategy: (voxel or FOV or field of view or resolution) and (CBCT or cone beam CT).

Studies comparing the influence of using two or more voxel sizes on CBCT-based diagnostic outcome qualified for inclusion. Only studies in which information regarding (1) image acquisition, (2) reconstruction protocols, (3) type of diagnostic task, and (4) presence of a gold standard for the true state of disease were selected. For studies based on categorical data, accuracy parameters such as sensitivity, specificity, likelihood ratio, or ROC curves should be present (at least one of them) to qualify for inclusion. For studies using quantitative data, agreement between measurements or accuracy of measurements should be present. All references were screened by one reviewer, and data extraction was verified separately by all authors.

Results

Review Search Results

The search strategy yielded 689 publications in MEDLINE (PubMed). The initial screening of the articles was conducted using the abstracts and keywords, but when these were unclear or unavailable, the full text was used.

Screening yielded 25 citations that potentially met the inclusion criteria, but an additional five papers were excluded. In one of them, although images were generated using diverse voxel sizes, this parameter was not assessed and interpreted in the results, which referred to other parameters (e.g., unit, FOV, and section thickness) [1]. One study tested various voxel sizes used to acquire the images (0.30 and 0.25 mm) but reconstructed the images using the same final resolution (0.25 mm), neglecting a direct comparison of voxel size [14]. The other studies were excluded because no gold standard was employed [15, 16] or because the evaluation was merely subjective of image quality [7].

Twenty publications were identified that assessed the influence of voxel size on CBCT-based diagnostic outcome, and in which the methodology/results fit the inclusion criteria. All included studies were ex vivo. Only one of the included studies cited the contrast settings used to evaluate the images [17]. Various diagnostic tasks were assessed, and according to it, the gold standard varied.

Among the 20 studies, 12 were based on categorical data. Of those, four assessed the detection of root fractures [18–21] (and used the clinical truth (an induced root fracture) as the gold standard), three assessed internal or external root resorption [22–24] also using the clinical truth as the gold standard, three assessed caries lesion detection [25–27] (and used sectioning and histology of the teeth as the gold standard), one assessed the detection of erosions in the temporomandibular joint [28] (using the clinical truth as the gold standard), and one assessed the presence of root canals in molars [29] using sectioning and histology of the teeth as the gold standard. The remaining eight studies were based on numerical outcomes measured in the images. Three studies measured 3D surface reconstructions [17, 30, 31] (and used micro-CT of the teeth as the gold standard), two measured the height and thickness of alveolar bone [11, 32], one assessed linear bone measurements (distance between established anatomical landmarks) [33], one measured the thickness of the soft tissue of the face [34], and one measured tooth and root length [35], and these last five studies used caliper measurements of the skulls as the gold standard. Six studies further compared the CBCT images in different resolutions to images acquired using intraoral radiographic systems [18, 21, 25–27, 35].

Information regarding the protocols of the studies is shown in Table 1. A compact overview of the assessment methods and results of the studies is shown in Table 2. From the studies assessed, it is clear that no protocol is yet defined for any of the evaluated diagnostic tasks.

Discussion

Under clinical conditions, the subjective image quality of CBCT-based images and the ability of CBCT to display various features are influenced by a number of variables, including the unit itself, the FOV, the tube voltage and current, the voxel size, and other technical factors [7, 36]. Many of these parameters can be varied according to the diagnostic task, but still no protocols have been established for specific diagnostic tasks in dentistry. In this way, the selection of parameters related to image generation and manipulation in CBCT imaging, including the selection of voxel resolution, seems to have been performed almost arbitrarily (“best guess” or availability in the equipment) [37, 38]. In opposition to that, protocols standardizing the selection of these parameters would have a direct impact on the radiation dose that the patient receives during examination (since they interfere with the scanning time), and a better definition would be essential in respecting the “ALARA” [39]. The intention of our review was to seek

Table 1 Summary of the diagnostic tasks, sample definition, and acquisition protocol of the images in the included studies

Study	Diagnostic task	Sample size	Unit (kV, mA; nd = not described)	Voxel size mm (FOV cm; nd = not described)
Wenzel at al. [21]	Detect transverse root fractures	69 human teeth, 34 with root fractures and 35 without	i-CAT[a] (nd)	0.125 (nd), 0.25 (nd)
Melo et al. [19]	Detect longitudinal root fractures	180 endodontically prepared human teeth, 90 with root fractures and 90 without. Further, each group of 90 teeth was divided in subgroups of 30 teeth—unfilled, filled with gutta-percha, or filled with a gold-alloy post	i-CAT[a] (120, 3–8)	0.2 (8), 0.3 (8)
Ozer [20]	Detect vertical root fractures	60 human teeth, 30 with root fractures and 30 without	i-CAT[a] (120, 5)	0.125 (4), 0.2 (4), 0.3 (4), 0.4 (4)
da Silveira et al. [18]	Detect vertical root fractures	60 single-rooted human teeth, 30 with root fractures and 30 without. Further, each group of 30 teeth was divided in subgroups of 10 teeth—unfilled, filled with gutta-percha, or filled with gutta-percha and a metal post	i-CAT[a] (120, 3–8)	0.2 (8), 0.3 (8), 0.4 (8)
Liedke et al. [24]	Detect external root resorption	59 human teeth, with surgically simulated root resorption	i-CAT[a] (120, 3–8)	0.2 (8), 0.3 (8), 0.4 (8)
Kamburoglu and Kursun [23]	Detect internal root resorption	60 human teeth, with surgically simulated root resorption	Iluma Ultra[b] (120, 3.8) 3D Accuitomo[c] (65, 2)	0.1 (14×21), 0.2 (14×21), 0.3 (14×21) 0.125 (6), 0.16 (8)
Dalili et al. [22]	Detect external root resorption	16 human tooth roots, with surgically simulated root resorption	NewTom VG[d] (110, automated)	0.125–0.150 (15), 0.2–0.24 (23)
Haiter-Neto et al. [26]	Detect approximal and occlusal caries lesions	200 approximal tooth surfaces (126 sound and 74 diseased) and 100 occlusal tooth surfaces (6 sound and 94 diseased)	NewTom 3G[d] (110, automated) 3DX Accuitomo[c] (60, 3)	0.16 (15), 0.25 (23), 0.36 (30) 0.125 (4)
Kamburoglu et al. [27]	Detect occlusal caries lesions	130 occlusal tooth surfaces (61 sound and 69 diseased)	Iluma Ultra[b] (120, 3.8)	0.1 (nd), 0.2 (nd), 0.3 (nd)
Cheng et al. [25]	Detect approximal caries lesions	90 approximal tooth surfaces (58 sound and 32 diseased)	ProMax 3D[e] (84, 6 and 12) DCT Pro[f] (90, 7.5)	0.16 (8), 0.32 (8) 0.2 (16×7), 0.3 (16×7)
Librizzi et al. [28]	Detect TMJ erosion	16 TMJs, with surgically simulated erosion spots	CB MercuRay[g] (120, nd)	0.2 (15), 0.3 (23), 0.4 (30)
Bauman et al. [29]	Detect mesiobuccal canals in maxillary molars	24 human maxillary molars, 22 with a second mesiobuccal canal	i-CAT[a] (120, 3–8)	0.125 (6×8), 0.2 (6×17), 0.3 (6×17), 0.4 (6×17)
Al-Rawi et al. [30]	Measure 3D reconstructions	2 fully dentate dry human jaws (maxilla and mandible)	Scanora 3D[h] (85, 8)	0.133 (6), 0.2 (7.5×10), 0.25 (7.5×14.5)
Maret et al. [31]	Measure 3D reconstructions	70 human teeth	Kodak 9500 3D[i] (90, 10) Kodak 9000 3D[i] (85, 2)	0.2 (9×15), 0.3 (18×20) 0.076 (5×3.7)
Damstra et al. [17]	Measure 3D reconstructions	10 dry human mandibles	KaVo 3D eXam[j] (120, nd)	0.25 (10), 0.4 (10)
Sun et al. [32]	Measure bone height and thickness	11 pig maxillae	i-CAT[a] (nd)	0.25 (nd), 0.4 (nd)
Patcas et al. [11]	Measure bone height and thickness	8 cadaver heads	KaVo 3D eXam[j] (120, 5)	0.125 (nd), 0.4 (nd)
Torres et al. [33]	Measure bone linearly	8 dry human mandibles	i-CAT[a] (120, nd)	0.2 (6), 0.25 (6), 0.3 (6), 0.4 (6)
Fourie et al. [34]	Measure soft tissue thickness	7 cadaver heads	KaVo 3D eXam[j] (nd)	0.3 (nd), 0.4 (nd)
Sherrard et al. [35]	Measure tooth and root length	52 human teeth	i-CAT[a] (120, 3–8)	0.2 (nd), 0.3 (nd), 0.4 (nd)

[a] Imaging Sciences International Inc., Hatfield, PA, USA

[b] 3M Imtec, Ardmore, OK, USA

[c] J Morita Mfg. Corp., Kyoto, Japan

[d] Quantitative Radiology, Verona, Italy

[e] Planmeca Oy, Helsinki, Finland

[f] VATECH Co. Ltd., Yongin-Si, South Korea

[g] Hitachi Medical, Kyoto, Japan

[h] Soredex Oy, Tuusula, Finland

[i] Carestream, Marne-la-Vallee, France

[j] KaVo Dental AG, Brugg, Switzerland

Table 2 Summary of the assessment methods and results of the included studies

Study	Assessment methods	Results
Wenzel at al. [21]	Six observers scored the images "with" or "without" fracture and fracture location (coronal, middle, apical third of the root). Images from an intraoral PSP system were also evaluated. The clinical truth was the gold standard	Sensitivity was higher in high-resolution CBCT images than in both the lower resolution CBCT and PSP images. The difference between CBCT in high and low resolution was highly significant, and also between CBCT in high resolution and PSP images. There was no difference between CBCT in the low resolution and PSP images
Melo et al. [19]	One observer scored the images "with" or "without" fracture. The clinical truth was the gold standard	Sensitivity was significantly higher for the 0.2-mm voxel resolution. Specificity values for CBCT were similar and did not depend on voxel resolution. The presence of gutta-percha or cast-gold posts reduced the overall sensitivity and specificity for both voxel resolutions
Ozer [20]	Three observers scored the teeth "with" or "without" fracture, in duplicate, based on images of three planes (axial, frontal, and sagittal). The clinical truth was the gold standard	Sensitivity and specificity were similar for all tested voxel sizes; the accuracy was inversely proportional to the voxel size, but with no statistical significance. The positive likelihood ratio was higher with 0.125- and 0.2-mm voxel size than with 0.3- and 0.4-mm voxel size
da Silveira et al. [18]	Three observers scored the images "with" or "without" fracture, in duplicate. Images from an intraoral radiographic method (conventional film), acquired with three different horizontal angles (orthogonal, mesial, and distal-angulated) were also evaluated. The clinical truth was the gold standard	Sensitivity, specificity, and accuracy were similar for 0.2 and 0.3-mm voxel size, for unfilled roots. Conventional radiographs showed similar results compared with 0.2 and 0.3-mm voxel CBCT in roots without endodontic treatment and metallic post. In teeth with root canal treatment or a post, the accuracy was higher for 0.2-mm voxel size
Liedke et al. [24]	One observer scored the images regarding the resorption size (small, medium, or large) and its location. The clinical truth was the gold standard	Sensitivity and specificity were similar and independent of voxel size. Likelihood ratio was 16 for 0.3-mm voxel, 12 for 0.2-mm voxel and 6.4 for 0.4-mm voxel size
Kamburoglu and Kursun [23]	Two observers scored the images, in duplicate, using a five-step scale to determine if there was internal resorption. The clinical truth was the gold standard	Intra- and inter-observer agreement was higher for the Accuitomo images. ROC curves showed the best results for Accuitomo 0.125-mm voxel size and the worst for Iluma 0.3 mm. No significant differences were found among the values for Accuitomo 0.125 mm, Accuitomo 0.16 mm, Iluma 0.1 mm and Iluma 0.2 mm
Dalili et al. [22]	One observer scored the images "with" or "without" resorption and its location (root surface/radicular third). The clinical truth was the gold standard	Diagnostic accuracy was high for the two tested modes of CBCT. The 0.125-mm voxel size was more accurate for small simulated resorption lesions located in the apical third and on lingual surfaces of teeth
Haiter-Neto et al. [26]	Six observers scored the images "with" or "without" caries lesions, using a five-step scale. Images from two intraoral radiographic methods (PSP and conventional film) were also evaluated. Histology was the gold standard	Diagnostic accuracy for detection of caries lesions was lower for NewTom 3G (in spite of the voxel size—0.16, 0.25, and 0.36 mm) than intraoral modalities and the 3DX Accuitomo in 0.125-mm voxel size. The Accuitomo 0.125-mm voxel size had a higher sensitivity than the intraoral systems for detection of lesions in dentine, but the overall true score was not higher
Kamburoglu et al. [27]	Four observers scored the images "with" or "without" caries lesions, in duplicate, using a five-step scale. Images from an intraoral CCD system were also evaluated. Histology was the gold standard	Voxel size did not affect the detection of occlusal caries. CBCT images based on 0.1-mm voxel size were the most, and intraoral images were the least accurate methods to diagnose superficial enamel, deep enamel, superficial dentine, and deep dentine caries
Cheng et al. [25]	Eight observers scored the images "with" or "without" caries lesions, in duplicate, using a five-step scale. Images from an intraoral PSP system were also evaluated. Histology was the gold standard	For enamel caries, no significant difference among CBCT images in 0.16, 0.32, 0.2, and 0.3-mm voxel size or among CBCT in all tested resolutions and PSP images was found. For dentinal caries, no significant difference among CBCT images in 0.16-, 0.32-, 0.2-, and 0.3-mm voxel size were found, but there was significant difference when comparing CBCT in all tested resolutions and PSP images
Librizzi et al. [28]		The agreement tended to be higher for 0.2-mm voxel size. The ROC analysis showed statistically

Table 2 (continued)

Study	Assessment methods	Results
	Two observers scored the images "with" or "without" erosion, in duplicate, using a five-step scale. The clinical truth was the gold standard	significant difference between the 0.2 and the 0.4-mm voxel size
Bauman et al. [29]	Seven observers evaluated videos made with all images from each tooth, scoring the absence, presence of one or two mesiobuccal canals. Histology was the gold standard	Observers were able to detect the correct number of mesiobuccal canals as voxel size decreased. There was a significant difference in accuracy among the tested resolutions except the two highest ones (0.2- and 0.125-mm voxel size)
Al-Rawi et al. [30]	One observer superimposed the CBCT-based surface reconstruction of tooth crows to the micro-CT-based 3D reconstruction. Micro-CT (isotropic 25 μm resolution) was the gold standard	CBCT reconstructions were larger than their micro-CT counterparts. For the CBCT-based images, differences were found between the 0.25 and 0.2-mm voxel sizes, but not between the 0.2 and 0.133 mm
Maret et al. [31]	One observer measured the images, in duplicate. Micro-CT (isotropic 41 μm resolution) was the gold standard	CBCT voxel sizes of 0.2 and 0.3 mm were not significantly different from 0.076 mm and micro-CT 41 μm, but CBCT slightly underestimated the volu metric measurements
Damstra et al. [17]	One observer measured the images, in triplicate. Digital caliper measurements were the gold standard	Statistically, all methods were similar. CBCT underestimated the reference values for approximately 60 % and overestimated for approximately 30 % of the measurements
Sun et al. [32]	Two observers measured the images, in duplicate. Digital caliper measurements were the gold standard	Alveolar bone thickness interfered in the accuracy of the bone height measurements. When the thickness was greater than the voxel size, the distance was overestimated. When it was equal or smaller than the voxel size, the distance was underestimated. For bone walls thinner than the voxel size, measures from both tested voxel sizes were different from the gold standard
Patcas et al. [11]	One observer measured the images, in duplicate. Digital caliper measurements were the gold standard	Both voxel resolutions were accurate compared to the gold standard, but the 99 % confidence interval for the absolute measurement error was higher in the lower resolution images
Torres et al. [33]	One observer measured the images, in duplicate. Digital caliper measurements were the gold standard	The majority of the measurements in CBCT underestimated the true measurements. There was no statistical difference between the tested voxel sizes regarding the overall measurement error
Fourie et al. [34]	Two observers measured the images, in triplicate, based on ten anatomic landmarks. Digital caliper measurements were the gold standard	CBCT measurements were reliable when compared to the true measurements. There was a slight but definite difference in the facial soft tissue thickness measurements between the two voxel sizes
Sherrard et al. [35]	One observer measured the images in duplicate. Images from two intraoral radiographic methods (CCD and conventional film) were also evaluated. Digital caliper measurements were the gold standard	Intraoral radiography measurements were less accurate than CBCT measurements, underestimating true root length and overestimating tooth length, although without statistical significance. Tooth length measurements for the 0.2-mm voxel size were significantly larger than the other two voxel sizes. The differences between the truth and CBCT measurements were not statistically significant

for a rationale on the impact of voxel size in CBCT-based image acquisition in order to suggest protocols for various diagnostic tasks in dentistry.

It was common in the studies that FOV and voxel size were evaluated together. It is known that larger FOVs may provide less sharp reconstructions because of the greater beam angulation in the superior and inferior volume area and reduced contrast-to-noise ratio [11]. In this review, included studies focused on voxel size, rather than the FOV size. Thus, the influence of FOV size per se was not assessed. Moreover, the influence of the software used to reconstruct the images, which may interfere in the quality of the final reconstructed image, was also not assessed, since the studies were based only in the native software of each unit.

Voxel size can influence the characteristics of the final image in several ways. It may influence noise in the orthogonal sections of an image: the smaller the voxel size, the greater the noise, but of course, the higher the spatial resolution [30]. Depending on the voxel size, radiopaque structures can become invisible. This can be caused by the partial volume averaging effect, which is a common computed tomography artifact and occurs when a voxel lies on the borders of two objects of different densities. This voxel will then reflect the average density of both objects rather than the true value of either object [3]. This “invisibility” of some structures could also be caused by the limitations in contrast resolution related to CBCT units, which determines the ability to distinguish two objects of similar densities and in close proximity [40, 41].

The diagnostic tasks evaluated in the studies included in this review were diverse. Four studies assessed the detection of root fractures [18–21] using the clinical truth as a gold standard. Wenzel et al. [21] and Melo et al. [19] suggested that high-resolution CBCT (voxel size smaller than 0.2 mm) should be used when root fracture is suspected but not visualized in a periapical image. In opposition to that, Ozer [20] and da Silveira et al. [18] did not find significant differences among voxel sizes ranging from 0.125 to 0.4 mm. Three studies evaluated the detection of simulated root resorption, also using the clinical truth as a gold standard. While Liedke et al. [24] tested three voxel sizes (0.4, 0.3, and 0.2 mm) and showed that they produced similar results, Dalili et al. [22] and Kamburoglu and Kursun [23] showed that high-resolution images (voxel size lower than 0.16 mm) were more accurate for the detection of artificially created internal root resorption.

Three studies evaluated caries lesion detection [25–27] and used histology of the tooth sections as a gold standard. Images from intraoral 2D systems were included for comparison. While Kamburoglu and colleagues [27] showed that voxel size did not affect the detection of occlusal caries lesions, Haiter-Neto and coauthors [26] showed that 0.125-mm voxel size (but not 0.16, 0.25, and 0.36 mm) provided more accurate lesion depth estimates for approximal lesions when compared to the histological gold standard than did the intraoral images. Cheng and coauthors [25] found diverse results for intraoral and CBCT-based images for dentinal caries (independent of voxel size) and suggested that CBCT should be a secondary imaging modality to be used when conventional views provide controversial results. For the detection of simulated temporomandibular joint erosion, Librizzi and coauthors [28] showed that images acquired with voxel size of 0.2 mm were significantly more accurate than those acquired using 0.4 mm. Similar results were found regarding the detection of mesiobuccal maxillary canals in molars [29].

Of the three studies which measured the accuracy of 3D reconstructions quantitatively, two used micro-CT of the teeth as a gold standard [30, 31]. Both studies found that CBCT-based images, independent of the voxel size, underestimated, though not statistically significant, the volumes measured with micro-CT. Micro-CT suffers from artifacts similar to those observed in CBCT, since the scanning technology is comparable. Both CBCT and micro-CT suffer from beam hardening artifacts [42]. As an example, specific materials such as gutta-percha and intra-canal metallic posts may contribute to artifact formation, decreasing the diagnostic quality of the image [19, 43]. However, the influence of beam hardening artifacts is lower in micro-CT compared with CBCT because it operates at a higher kVp and offers more uniform filtration as well as a higher spatial resolution [30]. The other study assessing 3D reconstructions used digital caliper measurements as a gold standard [17] and found no difference between the CBCT measurements in images with 0.4- and 0.25-mm voxel resolution compared with the anatomic truth.

Regarding the bone measurements made in CBCT images and compared to digital caliper measurements (as the gold standard), Sun and coauthors [32] (evaluating bone thickness) showed that measurements in images with a voxel size of 0.25 mm were closer to the direct measurements than 0.4 mm images. Patcas and colleagues [11] (evaluating both bone height and width) showed that 0.4-mm voxel images provided results as accurate as 0.125-mm voxel images. This finding is also in agreement with Torres and coauthors [33], who did not find differences between voxel sizes of 0.2, 0.3, and 0.4 mm, when evaluating linear bone measurements.

Regarding the thickness of soft tissue at ten facial landmarks, CBCT measurements were reliable when compared to the digital caliper measurements used as the gold standard. There were differences in the measurements obtained in 0.3- and 0.4-mm voxel images [34]. For tooth and root length measurements, no differences were shown between the gold standard (caliper) and CBCT-based measurements, independent of the selected voxel size (0.2, 0.3, or 0.4 mm) [35].

The relationship between dose and image quality should always be part of the decision making process for the establishment of imaging protocols. Despite the benefits and improvements in CBCT, it is still a source of ionizing radiation to the patient [44]. Voxel size is not only of overriding importance in terms of image quality but is also directly connected to the scanning and reconstruction times of CBCT images, along with other factors such as FOV, amperage, and tube voltage [39].

The benefits of a shorter scanning time (i.e., lower radiation exposure and less patient movement) might outweigh the poorer resolution [17]. It is important to emphasize that the ALARA principle should always be applied; thus, the protocol must be tailored to each case. Without sacrificing image quality and adopting the ALARA principle, the ability to select various voxel settings would be helpful in reducing the radiation dose to the patient [20]. None of the included studies directly evaluated the effective dose associated with the use of different voxel sizes. In one of the studies, this evaluation was made, but it connected the variation of FOV and voxel size at the same time, making it impossible to discuss whether the variation was caused by voxel size or FOV. [28] Another previous study showed similar results that smaller FOVs resulted in lower effective radiation doses and suggested that in general smaller FOVs should be used for dental imaging and larger FOVs restricted to cases where a wide view is required; however, no relationship between FOV and voxel size was commented [45].

One point that should be noticed is that most (with the exception of two [18, 19]) of the studies included in this review argued that the ex vivo ideal conditions for CBCT image generation, excluding metallic restorative materials, soft tissue, and other parameters that could complicate the CBCT-based diagnosis, were drawbacks. These factors, especially metallic materials that produce beam hardening artifacts, may influence the image quality and thus the diagnostic accuracy when a patient is examined and should therefore be considered in future studies.

Conclusion

The number of studies assessing the impact of voxel size variation on the diagnostic outcome in CBCT imaging in dentistry is small. Focusing on the studies, which used a gold standard method as validation for the diagnostic outcome, the lack of systematic information is clear. Although studies dealing with categorical data showed a tendency towards more accurate results connected to higher voxel resolutions, it is not yet possible to suggest general protocols for the different diagnostic tasks, in which CBCT can be applied. Further clinical studies in this area are needed in order to allow the professional radiological society to develop detailed guidelines for the use of CBCT.

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