RESEARCH ARTICLE

Image quality optimization using a narrow vertical detector dental cone-beam CT

¹Danieli Moura Brasil, ^{2,3,4,5}Ruben Pauwels, ⁶Wim Coucke, ¹Francisco Haiter-Neto and ^{2,3,7}Reinhilde Jacobs

¹Department of Oral Diagnosis, Division of Oral Radiology, Piracicaba Dental School, University of Campinas (UNICAMP), Piracicaba, Brazil; ²Department of Imaging and Pathology, Faculty of Medicine, Catholic University of Leuven, Leuven, Belgium; ³Department of Oral & Maxillofacial Surgery, University Hospitals Leuven, Leuven, Belgium; ⁴Department of Mechanical Engineering, Catholic University of Leuven, Leuven, Belgium; ⁵Department of Radiology, Faculty of Dentistry, Chulalongkorn University, Bangkok, Thailand; ⁶Freelance statistician, Leuven, Belgium; ⁷Department of Dental Medicine, Karolinska Institute, Stockholm, Sweden

Objectives: To determine the optimized kV setting for a narrow detector cone-beam CT (CBCT) unit.

Methods: Clinical (CL) and quantitative (QUANT) evaluations of image quality were performed using an anthropomorphic phantom. Technical (TECH) evaluation was performed with a polymethyl methacrylate phantom. Images were obtained using a PaX-i3D Green CBCT (Vatech, Hwaseong, Korea) device, with a large 21 × 19 and a medium 12 × 9 cm field of view (FOV), and high-dose (HD—ranging from 85 to 110 kV) and low-dose (LD—ranging from 75 to 95 kV) protocols, totaling four groups (21 × 19 cm HD, 21 × 19 cm LD, 12 × 9 cm HD, 12 × 9 cm LD). The radiation dose within each group was fixed by adapting the mA according to a predetermined dose-area product. For CL evaluation, three observers assessed images based on overall quality, sharpness, contrast, artefacts, and noise. For QUANT evaluation, mean gray value shift, % increase of standard deviation (SD), % of beam hardening and contrast-to-noise ratio (CNR) were calculated. For TECH evaluation, segmentation accuracy, CNR, metal artefact SD, metal object area, and sharpness were measured. Representative parameters were chosen for CL, QUANT, and TECH evaluations to determine the optimal kV based on biplot graphs. kV values of the same protocol were compared by the bootstrapping approach. The ones that had statistical differences with the best kV were considered as worse quality.

Results: Overall, kV values within the same group showed similar quality ($p > 0.05$), except for 110 kV in 21 × 19 cm HD and 85 kV in 12 × 9 cm HD of CL score; also 85, 90 kV in 21 × 19 cm HD and 75, 80 kV in 21 × 19 cm LD of QUANT score which were worse ($p < 0.05$).

Conclusion: At a constant dose, low and high kV protocols yield acceptable image quality for a narrow-detector CBCT unit.

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Introduction

Cone-beam CT (CBCT) has been increasingly used in many dental specialties. Manufacturers have developed systems able to cover different indications, offering a large variety of fields of view (FOV) and exposure parameters combinations which should provide good quality images as well as low radiation dose,^{1,2} in compliance with the ALARA (as low as reasonably achievable) principle.³

Image quality assessment of CBCT devices is sometimes focused on clinical image quality aspects,^{4–6} and sometimes on technical aspects.^{7–10} The use of different skull and jaw models to assess anatomical structures and landmarks from a clinical perspective limits the standardization of image quality evaluation. On the other hand, geometrical phantoms have been used allowing reproducible and objective measurements; these measurements can guide the evaluation of a scanner's performance but are often very difficult to link to clinical acceptability of an image.¹¹ Indeed, the use of clinical and technical image quality assessment is preferable to allow obtaining more conclusive and consistent data.

Moreover, CBCT image quality is intrinsically related to exposure parameters.^{11,12} A higher tube current-exposure time product (mAs) reduces image noise, while the manifestation of beam hardening artefacts is most affected by the tube voltage (kV). However, compared to mAs, the effect of kV is not so predictable due to a combination of different energy-dependent X-ray interactions affecting both detector signal and contrast.¹³ Obtaining a suitable image for clinical use involves the balancing between image quality and radiation dose parameters that are differently influenced by the exposure settings.

Recently, an impressive number of CBCT scanners have been introduced in the field of Dentomaxillofacial radiology trying to provide a balance between device cost, image quality, and radiation dose to the patient.¹⁴ Pax-i3D Green is a recent CBCT device developed by Vatech (Hwaseong, Korea), which provides a new design in which the X-ray source and detector are inside a gantry (rather than a U-arm). The unique aspect of this unit involved the use of a narrow (36.4 mm width) vertical detector and several consecutive fast rotations around the isocenter with incremental detector off-set. Another particular and convenient aspect of this unit for our purpose is that it allows the tube voltage to be selected between 60 and 110 kV, allowing for an in-depth investigation of the optimal kV for Dentomaxillofacial imaging, which is an issue that has only been partially resolved as of yet.^{13,15} No investigator has assessed image quality of this system. Thus, the purpose of this study was to use an optimization strategy for Dentomaxillofacial applications. In addition, this study proposed to use a consistent image quality assessment method by combining clinical, quantitative, and technical parameters.

Table 1 Technical specification of the PaX-i3D Green cone-beam CT

Voltage	60~110 kV (1 kV increment $\pm$ 10%)
Tube current	4~10 mA (0.1 mA increment $\pm$ 10%)
Exposure type	Continuous
Focal spot	0.5 mm
Filtration	2.5 mm Al + 2.0 mm Al (added)
Anode material	Tungsten
FOV size (cm)	8 $\times$ 8, 12 $\times$ 9, 17 $\times$ 11, 17 $\times$ 15 and 21 $\times$ 19
Detector type	CMOS photodiode array
Detector size	Active area: 310.4 $\times$ 36.4 mm
Reconstruction algorithm	FDK

Al, aluminium; CMOS, Complementary metal-oxide semiconductor; FDK, Feldkamp-Davis-Kress; FOV, field of view; kV, kilovoltage; mA, milliamperage.

Methods and materials

Clinical (CL) and quantitative (QUANT) evaluations were done using an anthropomorphic phantom (SK150, The Phantom Laboratory, Salem, NY) containing a natural human skull, upper cervical vertebrae, and urethane as soft-tissue simulating material. Technical (TECH) evaluation was performed with a polymethyl methacrylate (SEDENTEXCT IQ; Leeds Test Objects, Boroughbridge, UK) phantom filled with four inserts: 1 cm diameter cylinders of hydroxyapatite, air, aluminium, and an insert containing three small (~5.2 mm) titanium cylinders positioned in the central region. Phantoms were scanned using the PaX-i3D Green CBCT device, using a large 21 $\times$ 19 cm (0.3 mm voxel size) and a medium 12 $\times$ 9 cm (0.2 mm voxel size) FOV as well as high-dose (HD—ranging from 85 to 110 kV) and low-dose (LD—ranging from 75 to 95 kV) protocols, totaling four groups (21 $\times$ 19 cm HD, 21 $\times$ 19 cm LD, 12 $\times$ 9 cm HD, 12 $\times$ 9 cm LD). These FOV sizes were chosen for covering most of the clinical applications. Technical specifications of the PaX-i3D Green are listed in Table 1. The radiation dose within each group was fixed by adapting the mA for each protocol according to a predetermined dose-area product (DAP) value. Table 2 shows DAP range, kV and mA combinations for each protocol. All acquisitions for each group were registered automatically (through Maximization of Mutual Information) using elastix, ensuring that regions used for evaluation were matched exactly.¹⁶

CL evaluation

Three previously calibrated observers independently assessed images containing bone and dental structures. Corresponding images from the same group were shown simultaneously in a randomized order (Figure 1), in a darkened room on a 46" ED46D LCD display (Samsung, Seoul, South Korea).

CL evaluation was performed based on overall image quality, sharpness, contrast, artefacts, and noise, using

Table 2 DAP range, protocol number, kV and mA combination for each protocol group

FOV/voxel size	Dose level	DAP range (mGy.cm ²)			kV/mA			
21 × 19 cm/0.3 mm	HD	1233.5–1243.7	85/7	90/6.2	95/5.5	100/5.0	105/4.5	110/4.2
	LD	932.1–940	75/7	80/6.1	85/5.3	90/4.7	95/4.2	–
12 × 9 cm/0.2 mm	HD	520.1–524.4	85/7	90/6.2	95/5.5	100/5.0	105/4.5	110/4.2
	LD	393–396.4	75/7	80/6.1	85/5.3	90/4.7	95/4.2	–

DAP, dose-area product; FOV, field of view; HD, high-dose; LD, low-dose; kV, kilovoltage; mA, milliamperage.

four-point scales. To perform the descriptive analysis, all parameters were adjusted to the same crescent image quality scale, as described below: overall image quality, sharpness and contrast ranging from 1 to 4 (1-poor, 2-moderate, 3-good, 4-excellent), and presence of artefact and noise ranging from 1 to 4 [1- high quantity (useless), 2- moderate quantity, 3- low quantity, 4- no artefact/noise]. Apart from these scores, the observers were asked which image was best and worst for overall diagnosis for set of images shown simultaneously. All the evaluations were performed twice with a 2-week interval to assess intraobserver agreement.

QUANT evaluation

To objectively estimate the effect of kV on image quality by means of measuring artefact and noise, mean gray value (MGV) and its standard deviation (SD) were measured joining three regions of interest (ROI) within air, buccal soft-tissue (bst) and central soft-tissue (cst). These ROIs were traced on images of the following anatomical regions: alveolar level of upper jaw, upper teeth level, and lower jaw. Images of upper teeth level were selected due to a higher number of artefacts in the anthropomorphic phantom. ROIs were measured over five consecutive slices. The ROIs were reproduced exactly for all scans of a given FOV using a ROI Manager tool (ImageJ software, National

Institutes of Health, Bethesda, MD), thereby eliminating operator variability.¹³

Based on MGV and SD measurements,¹³ MGV shift, percentual increase of SD, contrast-to-noise ratio (CNR), and percentual beam hardening were calculated as the following formulas:

$$\text{MGV shift} = \frac{100 * (\text{MGV}_{bst} - \text{MGV}_{cst})}{(\text{MGV}_{cst} - \text{MGV}_{air})}$$

$$\% \text{ increase of SD} = 100 * \frac{\text{SD}_{bst}}{\text{SD}_{cst}} - 1$$

$$\text{CNR} = \frac{|\text{AVG}(\text{MGV}_{bst}, \text{MGV}_{cst}) - \text{MGV}_{air}|}{\sqrt{[\text{AVG}(\text{SD}_{bst}, \text{SD}_{cst})]^2 + \text{SD}_{air}^2}}$$

$$\% \text{ beam hardening} = 100 * \frac{(\text{MGV}_{bst} - \text{MGV}_{cst})}{(\text{MGV}_{cst} - \text{MGV}_{air})}$$

TECH evaluation

For TECH evaluation, segmentation accuracy, CNR, normalized metal artefact SD, metal object area, and full width at half maximum (FWHM) of the point spread function were measured using a fully automated procedure developed in-house.^{9,17} Table 3 shows the definition of each parameter used in each evaluation and its connotation in terms of image quality.

Statistical analysis

To assess the inter and intraobserver agreement, weighted κ statistics was done using IBM SPSS Statistics for Windows, (v. 22.0. IBM Corp., Armonk, NY). Descriptive statistics were used for each protocol group combining all observers together to show the most frequently chosen score for each parameter, and the percentage of best and worst kV chosen in the CL evaluation. To determine the optimal kV, a set of non-correlated parameters were selected using biplots based on principal components analysis for CL, QUANT, and TECH evaluations separately. Subsequently, for CL, QUANT, and TECH evaluations separately, the squared difference between each value and the corresponding optimal value, set per parameter was calculated and summed for the parameters that were chosen to be included. Differences between voltages were performed by comparing means. The standard error on the means was determined by a 100-fold bootstrap and a normal test using these means and their standard errors was applied to compare between voltages. $p \leq 0.05$

Figure 1 Clinical evaluation screen (axial reconstructions) of upper jaw region (FOV of 21 × 19 cm, high-dose protocols). (A) 85 kV/7 mA, (B) 105 kV/4.5 mA, (C) 90 kV/6.2 mA, (D) 100 kV/5 mA, (E) 95 kV/5.5 mA, (F). 110 kV/4.2 mA. FOV, field of view; kV, kilovoltage; mA, milliamperage.

Table 3 Parameters' definition and connotation in image quality

<i>Evaluation</i>	<i>Parameters</i>	<i>Definition</i>	<i>Connotation in image quality</i>
CL	Overall quality	Image quality in general, not considering a specific parameter	Higher = better
	Sharpness	Ability to discriminate small structures in an image	Higher = better
	Contrast	Ability to distinguish different densities in an image	Higher = better
	Artefact	Any distortion or error (like dark bands or dark streaks) unrelated to the real object	Higher = worse
QUANT	Noise	Graininess in appearance of a supposedly homogeneous structure	Higher = worse
	MGV shift	Mean of dark artefacts mainly from beam hardening but also from other phenomena	Higher = worse
	% of increase SD	Percentage of mixed artefacts (light and dark) normalized to the SD of a non-artefact region	Higher = worse
	% of beam hardening	Percentage of gray value shift between artefact and control region, divided by the difference between control region and air	Higher = worse
TECH	CNR	Difference in gray value between average of soft-tissues and air, divided by root sum of squares of the SDs	Higher = better
	Segm accur air	Segmentation accuracy error of an air-filled region	Higher = worse
	Segm accur Al	Segmentation accuracy error of an aluminium-filled region	Higher = worse
	CNR air	Contrast-to-noise ratio of air vs PMMA	Higher = better
	CNR Al	Contrast-to-noise ratio of aluminium vs PMMA	Higher = better
	CNR hydrox	Contrast-to-noise ratio of hydroxyapatite vs PMMA	Higher = better
	Norm metal SD	Normalized standard deviation of a homogeneous region containing metal artefacts	Higher = worse
	Metal object area	Average of the segmented cross-sectional areas of three small titanium cylinders	Higher = worse
	FWHM	Sharpness of an edge between air and PMMA	Higher = worse

Al, aluminium; CL, clinical; CNR, contrast-to-noise ratio; FWHM, full width at half maximum; MGV, mean gray value; Norm metal, normalized metal; PMMA, polymethyl methacrylate; QUANT, quantitative; SD, standard deviation; Segm accur, segmentation accuracy; TECH, technical.

was considered statistically significant. The voltages that had no statistical differences with the best kV chosen from the score graphs were considered as having the same quality.

Results

The weighted κ was determined for the scores of each clinical parameter separately. In Table 4, it can be seen that for the intraobserver comparisons, weighted κ values were found in the slight to moderate agreement range. While, for the interobserver comparisons, weighted κ values were found in the slight to fair agreement range.¹⁸

Figure 2 shows the graphs of the most frequently chosen score during clinical image quality evaluation, as well as the percentage in which each image was chosen as best or worst for each parameter and each kV. Overall, all parameters showed a moderate to good score. In addition, for low dose protocols, it is possible to see a tendency for higher kV protocols to be chosen as the best and lower kV protocols as the worst, while in high dose protocols this choice is better distributed between kV. In the large FOV, HD, and LD protocols exhibited similar image quality, being parameters scored between moderate and good in both. Meantime, in the medium FOV, variations are more evident, being overall

image quality and artefact greater scored in HD protocols, while in the LD protocols noise was perceived as high quantity in the lower kV.

The following parameters were chosen as representative to generate the scores: overall image quality, sharpness, and artefacts for CL evaluation; % of beam hardening, % increase of SD and CNR for

Table 4 Observer's agreement (weighted κ)

	<i>Observer</i>	<i>Observer 1</i>	<i>Observer 2</i>	<i>Observer 3</i>
Overall quality	Observer 1	0.52	0.05	0.34
	Observer 2		0.13	0.13
	Observer 3			0.37
Sharpness	Observer 1	0.28	0.20	0.21
	Observer 2		0.20	0.24
	Observer 3			0.14
Contrast	Observer 1	0.17	0.15	0.17
	Observer 2		0.33	0.02
	Observer 3			0.31
Artefact	Observer 1	0.37	0.29	0.35
	Observer 2		0.43	0.31
	Observer 3			0.29
Noise	Observer 1	0.40	0.14	0.25
	Observer 2		0.39	0.13
	Observer 3			0.53

Figure 2 Most frequently chosen scores for each parameter and percentage of choice of the best and worst image considering each kV from CL evaluation's descriptive analysis. Color lines represent each clinical parameter [overall image quality, sharpness, and contrast (1-poor, 2-moderate, 3-good, 4-excellent)], and presence of artefact and noise (1- high quantity/useless, 2- moderate quantity, 3- low quantity, 4- no artefact/noise)]. Chosen scores, see vertical left axis. Columns show the percentage of best and worst choice for each kV, see vertical right axis. CL, clinical; HD, high-dose; LD, low-dose; kV, kilovoltage.

QUANT evaluation; segmentation accuracy of air and aluminium, normalized metal artefact SD for TECH evaluation (Figure 3). Figure 4 shows the best kV for each score based on comparison between distances from ideal values. In the CL and QUANT scores, the

best kV of HD protocols presented lower distance from ideal value, *i.e.* better image quality, than the best kV of LD protocols. However, for the TECH score the same occurred only for the medium FOV.

Figure 3 Biplot graphs showing correlation between the parameters related to clinical (A), quantitative (B), and technical (C) evaluations. Parameters are represented by arrows. Components 1 and 2 mean the two directions that hold the most variability of the dataset. For every set of arrows that pointed into the same or opposite direction, one representative parameter was chosen to be used for the scores incorporating multiple parameters. Bolded parameters followed by * were chosen as representative for each evaluation (A, B, and C). CL, clinical; QUANT, quantitative; TECH, technical.

Figure 4 Relation between the distance from ideal values and kV for CL (A), QUANT (B), and TECH (C) evaluations. The closer to zero (on distance from ideal axis), the better image quality of that kV. Yellow points show the best kV for each group. Vertical axes represent the distance from ideal value. Horizontal axes represent the kV. Segmented and continuous lines represent each protocol group. CL, clinical; QUANT, quantitative; TECH, technical.

Based on the bootstrapping statistical approach and comparison between individual kV (Table 5), the ones that had no statistical differences with the best kV chosen from the score graphs were considered as the same quality.

In general, kV values within the same group showed similar quality ($p > 0.05$), except for 110 kV in 21×19 cm HD and 85 kV in 12×9 cm HD of CL score; also 85, 90 kV in 21×19 cm HD and 75, 80 kV in 12×9 cm LD of QUANT score which were worse ($p < 0.05$). Also, the choice of the best kV values presented in all the three evaluations revealed that, in the largest FOV, the range of best kV was reduced to the highest ones, while in the smaller FOVs, almost all kV values remained present (Figure 5).

Discussion

Confronted with the challenge of obtaining images with diagnostic quality acquired achieving the lowest radiation dose possible for the patient, it is of great importance to perform image quality assessments on CBCT machines, through the evaluation of image quality considering FOV, kV, mA, and subsequently radiation dose. In the present study, a commercially available CBCT scanner with a unique exposure geometry using a narrow vertical detector was assessed for clinical, quantitative, and technical image quality. From this combination of perspectives, we found that, at a fixed dose per scanning protocol, both low and high kV protocols can yield an acceptable image quality from a statistical point

of view, whereas distinct differences between protocols were found for individual image quality parameters.

Combining clinical and technical image quality assessment, using both anthropomorphic and geometric phantoms, enables for connecting the professional clinical view (*i.e.* direct application in diagnostic practice) with a quantification of technical image aspects, allowing for a degree of standardization,⁸ and achieving more conclusive and consistent data. Yet, dealing with so many variables and data generated by this set of assessments is a challenge. A biplot is a graphical representation of a multivariate data which reduces the dimensionality of large datasets, increasing interpretability and with minimal information loss.¹⁹ In our study, based on biplot graphs, correlation between several parameters from CL, QUANT, and TECH evaluations were found. The most representative parameters were thus selected to obtain scores considering the different image quality aspects.

Clinical image quality is essentially a descriptor of the subjective visual interpretation of an image that should convey enough information to allow a clinical decision to be made with an acceptable degree of certainty. Subjective evaluation is being considered as a factor of greater weight to assess the image quality in a task-based approach; however, the possibility of standardizing this method is limited.^{6,20} We found in CL score a slight difference in image quality between different kV settings at the same group. Because the dose within each group was fixed, and the available range for kV within the groups was limited, consistent and significant trends between kV and clinical image quality were not

Table 5 Comparison between individual kV

Protocol group	CL		QUANT		TECH	
	kV	p-value	kV	p-value	kV	p-value
21 × 19 cm HD	85–90	0.96	85–90	0.001	85–90	0.99
21 × 19 cm HD	85–95	0.45	85–95	0.001	85–95	0.99
21 × 19 cm HD	85–100	0.73	85–100	0.001	85–100	0.98
21 × 19 cm HD	85–105	0.68	85–105	0.001	85–105	0.92
21 × 19 cm HD	85–110	0.27	85–110	0.001*	85–110	0.93
21 × 19 cm HD	90–95	0.46	90–95	0.46	90–95	0.99
21 × 19 cm HD	90–100	0.68	90–100	0.15	90–100	0.98
21 × 19 cm HD	90–105	0.70	90–105	0.20	90–105	0.92
21 × 19 cm HD	90–110	0.22	90–110	0.02*	90–110	0.93
21 × 19 cm HD	95–100	0.24	95–100	0.50	95–100	0.98
21 × 19 cm HD	95–105	0.73	95–105	0.60	95–105	0.92
21 × 19 cm HD	95–110	0.03*	95–110	0.14	95–110	0.92
21 × 19 cm HD	100–105	0.43	100–105	0.87	100–105	0.94
21 × 19 cm HD	100–110	0.44	100–110	0.44	100–110	0.95
21 × 19 cm HD	105–110	0.10	105–110	0.35	105–110	0.99
21 × 19 cm LD	75–80	0.92	75–80	0.41	75–80	0.98
21 × 19 cm LD	75–85	0.43	75–85	0.02	75–85	0.95
21 × 19 cm LD	75–90	0.70	75–90	0.01	75–90	0.97
21 × 19 cm LD	75–95	0.98	75–95	0.001*	75–95	0.84
21 × 19 cm LD	80–85	0.49	80–85	0.11	80–85	0.98
21 × 19 cm LD	80–90	0.63	80–90	0.11	80–90	0.95
21 × 19 cm LD	80–95	0.95	80–95	0.01*	80–95	0.81
21 × 19 cm LD	85–90	0.24	85–90	0.81	85–90	0.92
21 × 19 cm LD	85–95	0.47	85–95	0.23	85–95	0.79
21 × 19 cm LD	90–95	0.69	90–95	0.14	90–95	0.86
12 × 9 cm HD	85–90	0.64	85–90	0.88	85–90	0.97
12 × 9 cm HD	85–95	0.12	85–95	0.45	85–95	0.96
12 × 9 cm HD	85–100	0.04*	85–100	0.06	85–100	0.92
12 × 9 cm HD	85–105	0.25	85–105	0.06	85–105	0.98
12 × 9 cm HD	85–110	0.18	85–110	0.05	85–110	0.96
12 × 9 cm HD	90–95	0.27	90–95	0.51	90–95	0.99
12 × 9 cm HD	90–100	0.12	90–100	0.06	90–100	0.95
12 × 9 cm HD	90–105	0.52	90–105	0.06	90–105	0.99
12 × 9 cm HD	90–110	0.40	90–110	0.05	90–110	0.98
12 × 9 cm HD	95–100	0.72	95–100	0.30	95–100	0.96
12 × 9 cm HD	95–105	0.56	95–105	0.32	95–105	0.97
12 × 9 cm HD	95–110	0.67	95–110	0.28	95–110	0.99
12 × 9 cm HD	100–105	0.29	100–105	0.94	100–105	0.94
12 × 9 cm HD	100–110	0.36	100–110	0.98	100–110	0.96
12 × 9 cm HD	105–110	0.85	105–110	0.91	105–110	0.97
12 × 9 cm LD	75–80	0.62	75–80	0.93	75–80	0.95
12 × 9 cm LD	75–85	0.88	75–85	0.54	75–85	0.99
12 × 9 cm LD	75–90	0.50	75–90	0.42	75–90	0.94
12 × 9 cm LD	75–95	0.74	75–95	0.33	75–95	0.90
12 × 9 cm LD	80–85	0.69	80–85	0.49	80–85	0.95
12 × 9 cm LD	80–90	0.82	80–90	0.39	80–90	0.99
12 × 9 cm LD	80–95	0.87	80–95	0.29	80–95	0.95
12 × 9 cm LD	85–90	0.54	85–90	0.75	85–90	0.94
12 × 9 cm LD	85–95	0.83	85–95	0.64	85–95	0.90
12 × 9 cm LD	90–95	0.71	90–95	0.92	90–95	0.96

CL, clinical; HD, high-dose; LD, low-dose; QUANT, quantitative; TECH, technical; kV, kilovoltage.

Bootstrapping statistical approach. Bolded numbers are comparisons between the best kV from score graphs and other kV values at the same protocol. (*) means statistical difference, $p < 0.05$.

Figure 5 Schematic representation of the material and methods resulting in the best kV values found for each protocol. Parameters followed by * were chosen to be used in the scores. Absent kV had lower image quality. Overall result shows the best kV values present in all the three evaluations for each protocol group. AI, aluminium; CL, clinical; CNR, contrast-to-noise ratio; FWHM, full width at half maximum; hydrox, hydroxyapatite; MGV, mean gray value; Norm metal, normalized metal; QUANT, quantitative; SD, standard deviation; Segm accur, segmentation accuracy; TECH, technical; kV, kilovoltage.

identified, partly due to the high subjectivity of this type of evaluation.⁶ This also can explain the slightly lower intra and interobserver agreement found in our study when compared to other ones evaluating subjective image quality.^{6,7,21–23} Images showed at the same screen during the observation section had very subtle differences, making it hard for observers to score each one. On the other hand, the tendency for higher kV protocols to be chosen as the best and lower kV protocols as the worst for low-dose protocols can be explained by the fact that, since acquired images in low-dose protocols have lower overall image quality, the increasing of the beam energy in higher kV can provide a visually impactful noise reduction and improvement of overall image quality.¹³ In high-dose protocols, the selection of the best and worst protocol was more evenly distributed between protocols with different kV, seeing that images acquired using high-dose protocol already had good overall quality.

The TECH scores showed no significant differences between kV within groups with identical FOV and dose, whereas differences were found between the four groups due to varying FOV size and dose level. Earlier

studies have found no changes in image uniformity²³ and segmentation accuracy²⁴ under different exposure parameters using geometrical phantoms, even without fixing radiation dose. This might be explained by the fact that the material from which the SEDENTEXCT phantom is made (polymethyl methacrylate) and its spatial distribution is homogeneous compared to bone and soft-tissues inside an anthropomorphic phantom. Therefore, the SEDENTEXCT phantom may not be able to represent subtle differences in clinical image quality due to varying amounts of X-ray scatter and beam hardening. In addition, parameters such as noise and sharpness are not expected to vary considerably when the dose, FOV, and voxel size are fixed. Using a polymethyl methacrylate, Loubele et al²⁴ found a small correlation between segmentation accuracy on a skull phantom and in the contrast phantom, which points out that information about diagnostic quality cannot be predicted by a physical phantom. For research involving variation of beam energy, the association with clinical evaluation using an anthropomorphic model may thus be preferred.²⁵

In contrast, in the QUANT evaluation, measurements were performed on scans obtained using an accurate head model. It was found that image quality may be improved by increasing the kV, since this higher kV may result in an increased contrast-to-noise ratio as well as reduced artefacts,¹³ just as Elkhateeb *et al*²⁶ also found less noise and more image uniformity when they used higher kV. In addition, these results show that for indications that require a large FOV the choice of higher kV values produce images with better quality, thus contributing to a good start for the study of the optimization of this device.

Although CBCT is widely used in a variety of dental specialties, still there is a scientific debate about the level of risk associated with this imaging modality.³ Hence, it is essential to apply the optimization principle whenever possible as an effort to reduce patient dose to the minimum level. X-ray tube current and exposure time are directly proportional to dose when other factors remain constant. The effect of kV on dose and image quality is more complex. kV is only altering beam energy, yet it may also vary the number of photons determining the resulting image and dose.¹³ In order to verify the influence of kV on image quality, it is necessary to fix the dose. As DAP has been related reasonably well with effective dose,³ in the present study, based on DAP, a dose range with as small as possible variation between dose of each kV was established for each scanning protocol, to maintain a minimal, also unavoidable, dose difference between kV within the same group. It was not possible to compare the full range of kV values at the same dose because of the limited mA range, so we split kV values into HD and LD groups, but with enough overlap between groups. Nevertheless, in clinical practice, the choice of using HD or LD protocols depends on the diagnostic task to be solved.

The current results are based on a novel CBCT unit which uses a unique acquisition geometry involving a narrow vertical detector and several consecutive rotations with incremental detector off-set. A benefit of such approach is that the primary-to-scattered ratio at the detector is increased, also it is possible to increase the width of the FOV while using a smaller area detector, thereby maybe reducing manufacturing costs.^{1,27,28}

Furthermore, future work should investigate whether applying image processing tools (*e.g.* high-sharpness filters *vs* low-noise filters) in the reconstruction process are needed to truly optimize the CBCT exposure. Considering that X-ray scatter magnitude as well as its angular distribution depends on beam energy, other CBCT units using a large-area flat panel detector may yield different results. Moreover, we introduced a novel method to combine clinical, quantitative, and technical evaluations, which was used for the first time for this narrow-detector CT optimization process. While the technical aspect may be more standardized, the clinical visual perception does not always correspond to the technical results, but it is more relevant and connected to the clinical radiodiagnostics. So, when striving for clinical optimization, it is necessary to start from a combined assessment of clinical and technical parameters, apart from considering dose aspects.

Conclusion

From a clinical and technical perspective, at a fixed dose per scanning protocol, both low and high kV protocols yield an acceptable image quality for a narrow-detector CBCT unit. Nonetheless, higher kV values (and correspondingly low mA values) should be preferred, as they lead to reduced noise and artefacts.

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Conflict of interest

Authors declares that there have no conflict of interest for this article.

References

1. Scarfe WC, Farman AG. What is cone-beam CT and how does it work? *Dent Clin North Am* 2008; **52**: 707–30. doi: <https://doi.org/10.1016/j.cden.2008.05.005>
2. Farman AG, Scarfe WC. The Basics of Maxillofacial Cone Beam Computed Tomography. *Semin Orthod* 2009; **15**: 2–13. doi: <https://doi.org/10.1053/j.sodo.2008.09.001>
3. Ludlow JB, Timothy R, Walker C, Hunter R, Benavides E, Samuelson DB, *et al*. Effective dose of dental CBCT—a meta analysis of published data and additional data for nine CBCT units44. doi. *Dentomaxillofac Radiol* 2015; **44**: 20140197. doi: <https://doi.org/10.1259/dmfr.20140197>
4. Kwong JC, Palomo JM, Landers MA, Figueroa A, Hans MG. Image quality produced by different cone-beam computed tomography settings. *Am J Orthod Dentofacial Orthop* 2008; **133**: 317–27. doi: <https://doi.org/10.1016/j.ajodo.2007.02.053>
5. Lofthag-Hansen S. Cone beam computed tomography radiation dose and image quality assessments. *Swed Dent J Suppl* 2010; 4–55.
6. Lofthag-Hansen S, Thilander-Klang A, Gröndahl K. Evaluation of subjective image quality in relation to diagnostic task for cone beam computed tomography with different fields of view. *Eur J Radiol* 2011; **80**: 483–8. doi: <https://doi.org/10.1016/j.ejrad.2010.09.018>

7. de Moura PM, Hallac RR, Seaward JR, Kane AA, Aguiar M, Raggio R, et al. Objective and subjective image evaluation of maxillary alveolar bone based on cone beam computed tomography exposure parameters. *Oral Surg Oral Med Oral Pathol Oral Radiol* 2016; **121**: 557–65. doi: <https://doi.org/10.1016/j.oooo.2016.01.019>
8. Bamba J, Araki K, Endo A, Okano T. Image quality assessment of three cone beam CT machines using the SEDENTEXCT CT phantom42: 20120445. doi: <https://doi.org/10.1259/dmfr.20120445>
9. Pauwels R, Stamatakis H, Manousaridis G, Walker A, Michielsen K, Bosmans H, et al. Development and applicability of a quality control phantom for dental cone-beam CT. *J Appl Clin Med Phys* 2011; **12**: 245–60. doi: <https://doi.org/10.1120/jacmp.v12i4.3478>
10. EzEldeen M, Stratis A, Coucke W, Codari M, Politis C, Jacobs R. As Low Dose as Sufficient Quality: Optimization of Cone-beam Computed Tomographic Scanning Protocol for Tooth Autotransplantation Planning and Follow-up in Children. *J Endod* 2017; **43**: 210–7. doi: <https://doi.org/10.1016/j.joen.2016.10.022>
11. Pauwels R, Seynaeve L, Henriques JC, de Oliveira-Santos C, Souza PC, Westphalen FH, et al. Optimization of dental CBCT exposures through mAs reduction. *Dentomaxillofac Radiol* 2015; **44**: 20150108. doi: <https://doi.org/10.1259/dmfr.20150108>
12. Rustemeyer P, Streubüher U, Suttmoeller J. Low-dose dental computed tomography: significant dose reduction without loss of image quality. *Acta Radiol* 2004; **45**: 847–53. doi: <https://doi.org/10.1080/02841850410001402>
13. Pauwels R, Silkoessak O, Jacobs R, Bogaerts R, Bosmans H, Panmekiate S. A pragmatic approach to determine the optimal kVp in cone beam CT: balancing contrast-to-noise ratio and radiation dose. *Dentomaxillofac Radiol* 2014; **43**: 20140059. doi: <https://doi.org/10.1259/dmfr.20140059>
14. Nemtoi A, Czink C, Haba D, Gahleitner A. Cone beam CT: a current overview of devices42: 20120443. doi: <https://doi.org/10.1259/dmfr.20120443>
15. Pauwels R, Jacobs R, Bogaerts R, Bosmans H, Panmekiate S. Determination of size-specific exposure settings in dental cone-beam CT. *Eur Radiol* 2017; **27**: 279–85. doi: <https://doi.org/10.1007/s00330-016-4353-z>
16. Klein S, Staring M, Murphy K, Viergever MA, Pluim JP. elastix: a toolbox for intensity-based medical image registration. *IEEE Trans Med Imaging* 2010; **29**: 196–205. doi: <https://doi.org/10.1109/TMI.2009.2035616>
17. Pauwels R, Stamatakis H, Bosmans H, Bogaerts R, Jacobs R, Horner K, et al. Quantification of metal artifacts on cone beam computed tomography images. *Clin Oral Implants Res* 2013; **24**(Suppl A100): 94–9. doi: <https://doi.org/10.1111/j.1600-0501.2011.02382.x>
18. Landis JR, Koch GG. The measurement of observer agreement for categorical data. *Biometrics* 1977; **33**: 159–74. doi: <https://doi.org/10.2307/2529310>
19. Jolliffe IT, Cadima J. Principal component analysis: a review and recent developmentsdoi. *Philos Trans A Math Phys Eng Sci* 2016; **374**: 20150202: 20150202: . doi: <https://doi.org/10.1098/rsta.2015.0202>
20. Liang X, Lambrichts I, Sun Y, Denis K, Hassan B, Li L, et al. A comparative evaluation of Cone Beam Computed Tomography (CBCT) and Multi-Slice CT (MSCT). Part II: On 3D model accuracy. *Eur J Radiol* 2010; **75**: 270–4. doi: <https://doi.org/10.1016/j.ejrad.2009.04.016>
21. Queiroz PM, Santaella GM, Capelozza ALA, Rosalen PL, Freitas DQ, Haite-Neto F. Zoom reconstruction tool: evaluation of image quality and influence on the diagnosis of root fracture. *J Endod* 2018; **44**: 621–5. doi: <https://doi.org/10.1016/j.joen.2017.10.011>
22. Vasconcelos TV, Neves FS, Queiroz de Freitas D, Campos PS, Watanabe PC. Influence of the milliamperage settings on cone beam computed tomography imaging for implant planning. *Int J Oral Maxillofac Implants* 2014; **29**: 1364–8. doi: <https://doi.org/10.11607/jomi.3524>
23. Choi JW, Lee SS, Choi SC, Heo MS, Huh KH, Yi WJ, et al. Relationship between physical factors and subjective image quality of cone-beam computed tomography images according to diagnostic task. *Oral Surg Oral Med Oral Pathol Oral Radiol* 2015; **119**: 357–65. doi: <https://doi.org/10.1016/j.oooo.2014.11.010>
24. Loubele M, Jacobs R, Maes F, Denis K, White S, Coudyzer W, et al. Image quality vs radiation dose of four cone beam computed tomography scanners. *Dentomaxillofac Radiol* 2008; **37**: 309–19. doi: <https://doi.org/10.1259/dmfr/16770531>
25. Pauwels R, Jacobs R, Bogaerts R, Bosmans H, Panmekiate S. 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. doi: <https://doi.org/10.1016/j.oooo.2015.10.017>
26. Elkhateeb SM, Torgersen GR, Arnout EA. Image quality assessment of clinically-applied CBCT protocols using a QAT phantom. *Dentomaxillofac Radiol* 2016; **45**: 20160075. doi: <https://doi.org/10.1259/dmfr.20160075>
27. Molteni R. Prospects and challenges of rendering tissue density in Hounsfield units for cone beam computed tomography. *Oral Surg Oral Med Oral Pathol Oral Radiol* 2013; **116**: 105–19. doi: <https://doi.org/10.1016/j.oooo.2013.04.013>
28. Pauwels R, Theodorakou C, Walker A, Bosmans H, Jacobs R, Horner K, et al. Dose distribution for dental cone beam CT and its implication for defining a dose index. *Dentomaxillofac Radiol* 2012; **41**: 583–93. doi: <https://doi.org/10.1259/dmfr/20920453>