RESEARCH ARTICLE

Image quality optimization of narrow detector dental computed tomography for paediatric patients

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Objectives: Dental CBCT exposure parameters should be optimized according to patient-specific indications, mainly for children that are most vulnerable to harmful effects of ionizing radiation. The aim of this study was to determine optimized kV settings for paediatric acquisitions for a dental CBCT device.

Methods: Clinical and quantitative evaluations of image quality were performed using 5 and 10 years old (y/o) anthropomorphic phantoms. Technical evaluation was performed with the SEDENTEXCT-IQ phantom. Images were obtained using a PaX-i3D Green CBCT (Vatech, Korea) device, combining tube voltages ranging from 85 to 110 kV and 2 fields of view (FOVs: 21 × 19 and 12 × 9 cm), while maintaining the radiation dose fixed by adjusting the mA accordingly. Clinically, observers assessed images based on overall quality, sharpness, contrast, artefacts, and noise. For quantitative evaluation, mean grey value shift, % increase standard deviation, % beam-hardening and contrast-to-noise ratio were calculated. For technical evaluation, segmentation accuracy, contrast-to-noise ratio and full width at half maximum were measured. Biplot graphs were used to choose representative parameters, from which the best kV was selected for each protocol and evaluation. kV values that had no statistical differences ($p > 0.05$) with the best kV chosen were considered as having the same quality.

Results: Clinically, 95 kV was found as a cut-off value. From the quantitative aspect, 85 kV ($p < 0.05$) showed the worst quality, except in 12 × 9 cm 5 y/o. Technically, 85 and 110 kV in the large FOV showed significantly worse quality for the large FOV.

Conclusion: For paediatric indications, 95 kV or higher (and correspondingly low mA values) was found as optimal.

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Introduction

Optimization is defined by the International Commission on Radiological Protection as the principle that

patient exposure should be kept as low as reasonably achievable, taking into account economic and societal factors.^{1,2} With the increasing use of CBCT for dentomaxillofacial diagnostics,^{3,4} concerns about radiation risks related to using this imaging modality have increased, particularly for paediatric patients due to

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their higher vulnerability to harmful effects of ionizing radiation.⁵

CBCT units capable of providing “low dose” protocols by means of adjustments to rotation arc, mA, kV, number of basis images, beam collimation, or a combination thereof, have been introduced in the market.⁴ However, this should not result in a significant drop in image quality, in accordance with the principle of optimization, which is especially relevant for devices that use innovative technologies. In a recent study, optimization was performed for a narrow-detector CBCT for adult indications,⁶ however its results cannot be applied to children since the balance between kV, mAs and image quality is expected to be dependent on head size.⁷

Recommendations and clinical guidance notes for the main CBCT indications in paediatric dentistry have been published, considering the paediatric vulnerability to stochastic biological effects and the still incomplete information on the required indication-oriented image quality.^{8,9} In addition, many studies have been developed to establish CBCT exposure protocols for paediatric patients according to clinical indications.^{2,9–12} In terms of indication-specific optimization, kV and mAs levels should be selected according to the required image quality and patient size.⁷ As optimization can be somewhat complicated, it is suggested to be performed, firstly, by determining the optimal kV at a given radiation dose level, then, using this optimal kV, reducing mAs to the lowest acceptable level for clinical imaging.¹³

The current challenge in optimization of CBCT is to decrease radiation dose without drastically reducing image quality and diagnostic information. Since image quality is observer-dependent, measurement and comparison of image quality across CBCT units is complex. Different methodologies can be applied to investigate image-based measurement accuracy, including geometric^{14–16} or anthropomorphic phantoms, such as dry skulls with soft tissue simulation^{17,18} or cadaver heads.^{19,20} Although using these materials allows studying qualitative and quantitative aspects of image quality, the obtained data must be further managed to allow clinical recommendations for indication-oriented and patient-specific optimization. Such approach may require further machine-specific examinations.

The aim of this study was to conduct an optimization by determining proper kV settings for dental CBCT for dentomaxillofacial paediatric acquisitions for a narrow detector device using a consistent image quality assessment method.

Methods and materials

CBCT unit and phantoms

The PaX-i3D Green Premium dental CBCT unit (Vatech, Hwaseong, South Korea) was used in this study. For clinical and quantitative evaluations of image quality, 5- and 10-year-old (y/o) phantoms developed and validated for use in paediatric dentomaxillofacial

Figure 1 Phantoms. 5 y/o phantom (A)²¹; axial image of 5 y/o upper jaw region (B); 10 y/o phantom (C)²¹; axial image of 10 y/o upper jaw region (D); SEDENTEXCT-IQ phantom (E); axial image of SEDENTEXCT-IQ with three alternatively empty peripheral columns and hydroxyapatite, air and aluminium cylinders placed in the central column (F).

radiology research by the DIMITRA (“Dento-maxillofacial paediatric imaging: an investigation towards low-dose radiation induced risks”) European research project consortium²¹ were used. To perform a complementary technical evaluation of image quality, a polymethyl methacrylate (PMMA) phantom (SEDENTEXCT-IQ; Leeds Test Objects, Boroughbridge) was used, filled with three inserts, containing 1 cm diameter cylinders of hydroxyapatite, air and aluminium positioned in the central region. The phantom is modular, having one central and six peripheral columns for insert placement. The aforementioned inserts were placed in the central column, and three of the six peripheral columns were kept empty, whereas the other columns were filled up with PMMA inserts. As a result, the phantom was similar to a small patient in terms of X-ray absorption and scatter⁷ (Figure 1).

Table 1 Acquisition protocols

FOV (cm)	Exposure time (s)	Voxel size (mm)	DAP range (mGy.cm ²)	kV & mA					
21 × 19	18	0.3	1233.5–1243.7	85 & 7	90 & 6.2	95 & 5.5	100 & 5.0	105 & 4.5	110 & 4.2
12 × 9	13.9	0.2	520.1–524.4	85 & 7	90 & 6.2	95 & 5.5	100 & 5.0	105 & 4.5	110 & 4.2

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

Acquisition protocols

Phantoms were scanned using a large and a medium field of view (FOV) and exposure parameters displayed in Table 1.

Image quality evaluation

All acquisitions from different protocols were first automatically aligned to the same position with the elastix software, using maximization of mutual information as a registration metric.²²

For clinical assessment, axial, sagittal and coronal images of upper jaw, lower jaw and temporomandibular joint were evaluated by three calibrated observers experienced in radiological analysis of CBCT exams. All images from the same region acquired using the same FOV were presented in a random order on the same screen (Figure 2), in PowerPoint software (Microsoft

Corp, Seattle, WA), with image compression disabled, and viewed on a 46" ED46D LCD display (Samsung, Seoul, South Korea) in a darkened room, for all observers together, to ensure it was done under the same conditions. Observers were asked to score each image using a 4-point scale: 1, poor; 2, moderate; 3, good; 4, excellent, regarding overall image quality, sharpness, contrast; and 4, high quantity (useless), 3, moderate quantity, 2, low quantity, 1, no artefact/noise, regarding artefacts and noise. To perform the descriptive analysis, all parameters were adjusted to the same crescent image quality scale. For a more elaborate explanation, refer to the previous study.⁶ All sets of images were evaluated twice with a 2-week interval.

For the quantitative evaluation, ImageJ software (National Institutes of Health, Bethesda, MD) was used to measure the mean grey value and its standard deviation in four regions of interest, over five consecutive

Figure 2 Clinical evaluation screen (sagittal reconstructions) of upper and lower jaw anterior region (FOV of 12 × 9 cm, 5 y/o phantom). (A) 105 kV & 4.5 mA, (B) 95 kV & 5.5 mA, (C) 90 kV & 6.2 mA, (D) 100 kV & 5 mA, (E) 85 kV & 7 mA, (F) 110 kV & 4.2 mA. FOV, field of view.

Figure 3 Axial reconstruction of 5 y/o lower jaw with ROIs used in quantitative evaluation. ROI₁ in bst, ROI₂ in lst, ROI₃ in cst, ROI₄ in air. bst, buccal soft-tissue; cst, central soft-tissue; lst, lingual soft-tissue; ROIs, regions of interest.

slices, containing buccal soft-tissue, lingual soft-tissue, central soft-tissue and air (Figure 3). Mean grey value (MGV) shift, percentual increase of standard deviation, contrast-to-noise ratio (CNR) and percentage of beam hardening caused by jaw bone were calculated using the following formulas:

$$MGV\ shift = \frac{100 \cdot (MGV_{bst} - MGV_{cst})}{(MGV_{cst} - MGV_{air})} \quad (1)$$

$$\% \ increase\ of\ SD = 100 \cdot \frac{SD_{bst}}{SD_{cst}} - 1 \quad (2)$$

$$CNR = \frac{|(MGV_{bst}, MGV_{cst})/2 - MGV_{air}|}{\sqrt{[(SD_{bst}, SD_{cst})/2]^2 + SD_{air}^2}} \quad (3)$$

$$\% \ beam\ hardening = 100 \cdot \frac{(MGV_{bst} - MGV_{lst})}{(MGV_{cst} - MGV_{air})} \quad (4)$$

For the evaluation of image quality based on technical parameters, CNR for air vs PMMA (CNR_{Air}), aluminium vs PMMA (CNR_{Al}) and hydroxyapatite vs PMMA (CNR_{Hydrox}), segmentation accuracy of air ($Segm_{Air}$) and aluminium ($Segm_{Al}$), and full width at half maximum (FWHM) of the point spread function were measured using a fully automated procedure developed in-house.^{15,23} The technical parameters are described in more detail in a previous study.⁶

Statistical analysis

Intra- and interobserver agreement were assessed using a weighted κ , calculated with IBM SPSS Statistics for Windows (v. 22.0. IBM Corp., Armonk, NY). Descriptive statistics were carried out for clinical evaluation data combining scores of all observers to allow demonstrating the most frequently chosen score for each parameter and kV values. To determine the optimal kV, biplot graphs based on main component analysis were used to select representative parameters, which are represented by arrows (Figures 4 and 5). Strongly positively correlated variables are represented by arrows that point into the same direction, whereas negatively correlated variables point into the opposite direction. For every set of arrows that points into the same or opposite direction, one representative parameter was taken to be used in the score graphs to compare kV for clinical, quantitative and technical evaluations. Differences between voltages were evaluated by comparing means. By a 100-fold bootstrap the standard error on

Figure 4 Flowchart of the method used to perform the statistical analysis. CL, clinical; P (1–5), parameters.

Figure 5 Biplot graphs exhibiting correlations between parameters related to specific phantoms and evaluations, 5 y/o clinical evaluation (A), 10 y/o clinical evaluation (B), 5 y/o quantitative evaluation (C), 10 y/o quantitative evaluation (D). Parameters are represented by arrows. Components 1 and 2 indicate the two directions that hold the highest variability of the dataset. For every set of arrows that point to the same or opposite direction, one representative parameter was chosen to be used for the scores incorporating multiple parameters. Bolded parameters marked by * were chosen as representative for each evaluation.

the means was determined and a normal test using these means and their standard errors was applied to compare the voltages. Significant differences were defined at $p \leq 0.05$. Kilovoltages that had no statistical differences with the best kV chosen from the score graphs were considered as having the same quality. Figure 4 shows the flowchart of the applied statistical method.

Results

Average κ values representing intra- and interobserver agreement were 0.50 (moderate) and 0.34 (fair),²⁴ respectively (Table 2).

Descriptive analysis of the clinical evaluation data showed that the most common score for overall image quality, contrast and sharpness was “good” (score 3), whilst for noise and artefacts it was “low quantity” (score 2) (Table 3). For kV values higher than 95 kV, the percentage of these scores remained relatively stable,

Table 2 Intra- and interobserver agreement (weighted κ)

Observer	Observer 1	Observer 2	Observer 3
Observer 1	0.58	0.39	0.37
Observer 2		0.47	0.28
Observer 3			0.45

Table 3 Percentage of the most frequently chosen score for each clinical parameter and kV

kV	Score	Percentage of the most frequently chosen score				
		Overall	Sharpness	Contrast	Artefacts	Noise
85	Good / low quantity	44.1	35.7	36.9	71.4	45.3
90		51.2	39.3	36.9	70.3	50.0
95		61.9	51.2	42.9	71.4	54.8
100		59.5	53.6	45.0	71.4	51.2
105		59.5	51.2	45.3	72.6	50.0
110		59.5	51.2	44.5	69.1	48.8

Kilovoltage, kV.

indicating that this may represent a cut-off for clinical analysis.

By using biplot graphs and statistical comparisons, for the 5 y/o analysis, overall image quality, noise and contrast were chosen as representative parameters from the clinical evaluation; CNR and percentual of increase of standard deviation were chosen from the quantitative evaluation. For the 10 y/o analysis, overall image quality, noise and sharpness were chosen from the clinical evaluation, and CNR, percentual of beam hardening and mean grey value shift were chosen from the quantitative evaluation (Figure 5).

Based on the distance from ideal values, in which lower values signify better image quality, the best kV values were chosen on the score graphs (Figure 6). The most common optimal kV was 110 kV ($n = 3$), followed by 105 and 95 kV ($n = 2$), and 100 kV ($n = 1$).

Figure 7 shows the effect of tube voltage on the behaviour of the technical parameters. In general, differences were small. Segmentation accuracy was not affected by kV. CNR_{Air} and CNR_{Al} showed a positive linear relation with kV, but CNR_{Hydrox} showed a negative relation. FWHM did not show a linear behaviour. From biplot statistics, FWHM and CNR_{Al} were chosen as representative. Based on the distance from ideal values on the score graph, 105 kV was chosen as optimal.

For the clinical evaluation, kV values showed similar quality ($p > 0.05$) compared with the best kV chosen from the score graph for each FOV, while for the quantitative aspect, 85 kV showed the worst quality for 12×9 cm 10 y/o ($p = 0.019$), 21×19 cm 5 y/o ($p = 0.013$) and 10 y/o ($p = 0.016$). For the technical evaluation, 85 ($p = 0.018$) and 110 kV ($p = 0.016$) for the large FOV showed the worst quality (Supplementary Table 1). In general, these results reveal that, quantitatively and technically 85 kV had the worst image quality; nevertheless, this was not significantly reflected in the clinical aspect.

Discussion

In this paper, at a fixed radiation dose, image quality of paediatric CBCT was assessed and compared for different combinations of kV and mA. Generally, the lower kV

Figure 6 Relationship between the distance from ideal values and kV for 5 y/o clinical score (A), 10 y/o clinical score (B), 5 y/o quantitative score (C), 10 y/o quantitative score (D). Vertical axes in each box represent the distance from the ideal value. Horizontal axes in each box represent kV values. Dotted and continuous lines represent each FOV. The closer to zero (on distance from ideal axis), the better the image quality of that kV. Filled black points indicate the best kV for each FOV. FOV, field of view; kV, kilovoltage.

images were more affected by noise and artefacts in the quantitative and technical evaluations. This result is in accordance to previous studies that found lower image noise using higher kV.^{6,7,16,25} Therefore, a higher kV should be used in combination with a lower mA according to the optimization process.

The CBCT device used in this study allows to select tube voltages higher than 90 kV (60–110 kV). Since Pauwels *et al*⁷ found that, within the 60–90 kV range, 90 kV resulting in a lower noise-matched dose than lower

kV settings even for small patients, we used the range of 85 to 110 kV to check if higher kV (with lower mA) may be optimal for paediatric patients. We found that acquisitions using 85 kV were more affected by noise and artefacts, presenting worst image quality, while clinically images from 95 to 110 kV presented better quality. This may be due to higher kV producing a combination of higher beam penetration, different degrees of scatter and lower beam hardening resulting in a greater image quality. However, in the technical aspect, for the larger

Figure 7 Effect of kV on technical parameters (A–F), where vertical axes represent parameter values and horizontal axes represent tube voltage. Biplot graph (G) displaying correlations between parameters related to SEDENTEXCT-IQ phantom. Parameters are represented by arrows. Components 1 and 2 indicate the two directions that hold the highest variability of the data set. For every set of arrows that point to the same or opposite direction, one representative parameter was chosen to be used for the scores incorporating multiple parameters. Bolded parameters marked by * were chosen as representative for each evaluation. Score graph (H) displaying the relation between the distance from ideal values and kV, where vertical axes represent the distance from ideal value and horizontal axes represent the kV. The closer to zero (on distance from ideal axis), the better image quality of that kV. Filled black points indicate the best kV for each FOV. For all images dotted and continuous lines represent each FOV. FOV, field of view. kV, kilovoltage.

FOV, not only 85 kV, but also 110 kV had worse image quality, implying that there may be an upper threshold for tube voltages that yield a high image quality per unit of dose. This fact associated with the stagnation of image quality in the visual perception found from 95 kV upwards, as well as 85 or 90 kV often showing worse quality, 95 kV was defined as a cut-off value for kV.

From the moderate intraobserver agreement and the fair interobserver agreement, it could be seen that the observers' scoring was highly subjective, which is inherent to this type of evaluation. Other studies using anthropomorphic or skull phantoms reported moderate^{18,26} or slight to substantial¹³ observer's agreement, but arranged slices in a stack order,¹³ asked about specific anatomical structures^{13,18} and allowed the adjustment of brightness and contrast.¹⁸ Thus, by combining a clinical and quantitative/technical evaluation, it is more feasible to recognise how images are affected by exposure parameters.

Additionally, the evaluation of clinical image quality showed no specific trend, being susceptible to partiality. In the present study, the observers' perception of subjective parameters was similar among kV values, implying that the image quality is mainly dictated by the dose level. De Moura *et al*^{19,19} showed that 90% of images at varying

kV and mA scored as "good" or "very good," which reinforce our findings. As revealed in a discussion with the observers of the present study, images with different kV presented on the same screen were very similar, making it quite challenging to spot differences in the parameters between the various images presented.

Faced with the inherent subjectivity of subjective evaluation, technical image quality parameters can be measured in a more standardized way.^{19,25} Yet, the latter cannot be strictly connected to clinical image quality. To merge the clinical visual perception with the technical data, we used a unique evaluation set-up⁶ combining clinical, quantitative and technical aspects to consistently perform the optimization process. The biplot graphs confirmed the higher prediction power of the objective results, in contrast with the subjectivity of the clinical evaluation, as also found when evaluating exposure protocols for adults.⁶

Regarding the technical evaluation, parameters that had the same behaviour under varying kV showed high intercorrelation in the biplot graph. Unlike CNR, FWHM and segmentation accuracy showed no consistent relation with kV, as they are influenced by a number of additional factors such as the voxel size, focal spot size, number of projections and reconstruction kernel.^{15,27} However, CNR_{Hydrox} had an opposite behaviour compared to CNR_{AI}

and CNR_{Air} . In general, the numerator of the CNR formula is expected to decrease at higher kV due to the convergence of attenuation coefficients for different materials at higher X-ray energies, whereas the denominator (*i.e.* the noise) is expected to decrease as well owing to the higher signal-to-noise ratio at the level of the detector. Since Al and Air vs PMMA contrast is inherently high, the CNR increased at higher kV due to the lower noise overcompensating for the relatively small loss in contrast. On the other hand, the shift in contrast between Hydrox vs PMMA at higher kV was the dominant factor in the CNR, outweighing the corresponding decrease in noise. Therefore, for clinical applications the kV needs to be adapted accordingly to the contrast between tissues related to the diagnostic task. FWHM and CNR_{Al} were statistically selected as representative, in which lower values of the first and higher values of the latter represent better image quality. Considering these parameters, intermediate kV values presented better results.

While image optimization for paediatric patients is particularly crucial, the concept can be extended for all patients. Once the ideal kV range has been established for which noise and artefacts are minimized,^{16,25} the next steps should be to determine the lowest mA level that results in an acceptable image quality for paediatric

patient-specific diagnostic tasks, as well as to compare these results with those of different CBCT devices.

Conclusion

For the CBCT device used in this study, 95 kV or higher was optimal for paediatric dentistry indications. It is suggested to achieve low-dose protocols by reducing the mA according to paediatric patient-specific diagnostic tasks.

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