TECHNICAL REPORT

Quantitative assessment of variation in CBCT image technical parameters related to CBCT detector lateral-offset position

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Objectives: To assess the effect of CBCT detector position (aligned/lateral-offset) on image technical parameters (mean voxel value - MVV, standard deviation of voxel value (SDVV) distribution), comparing peripheral regions of interest (ROIs) to the central ROI in CBCT volumes.

Methods: 40 CBCT volumes of a wax phantom were acquired in six units with aligned and/or lateral-offset detectors: Cranex 3Dx (CRA), Ortophos SL (ORT), Picasso Trio (PIC), Promax 3D Mid (PRO), Scanora 3D (SCA), and X1. Four image-acquisition protocols used an aligned detector, and four a lateral-offset detector. In each volume, 13 ROIs (12 peripheral and 1 central) were evaluated. MVV and SDVV of the peripheral ROI were compared to those of the central ROI in the volume. MVVD (the difference in percentage, between the MVV of a peripheral and the central ROI) was calculated.

Results: For aligned-detectors, MVV increased (ORT and PRO) or decreased (CRA and X1) in the ROIs farther from the centre. For lateral-offset detectors, ROIs farther from the centre showed increased MVV. SDVV for most aligned detectors was lower, the nearer the ROI was to the centre. For lateral-offset detectors, it was lower for the peripheral ROIs, except with PIC. Range for MVVD was -32.8% to 22.8% for units with aligned detectors, and -20.7% to 69.5% for lateral-offset detectors.

Conclusion: Lateral-offset detectors to acquire CBCT images significantly change SDVV distribution within the field-of-view, and lead to MVVD with increased range, compared to aligned detectors. This must be taken in consideration in the clinic, if voxel-value dependent measurements are to be performed.

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Introduction

CBCT volumes are acquired using an X-ray source and a detector that rotates around the patient, acquiring multiple two-dimensional images, often called basis images or raw projections, that are posteriorly

reconstructed into a three-dimensional volume.¹⁻³ Due to the divergence of the X-rays, the cone- or pyramidal-shaped beam¹ emitted by the source hits the detector (*i.e.* image receptor) with different angulations. The central beam (perpendicular to the detector) provides higher accuracy during image reconstruction,⁴ while the peripheral beams, which have more acute angles, cause variations in the reconstruction process and may

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degrade image quality, *i.e.* introduction of noise and artefacts.^{1,5,6}

Multiple studies have been conducted considering the variations in voxel values depending on the position of the patient/object in the field of view (FOV).^{7–11} However, little attention has been paid to how the basis images are acquired, focusing mainly on the final reconstructed volume. This can be related to the fact that data available for these projections is rarely provided by the manufacturers, and to difficulties to access the images. If the traditional FDK algorithm was used, one could speculate that the central region in the volume (*i.e.*, its midplane) is reconstructed based on the region where the central X-ray beam hits the detector perpendicularly, while the peripheral parts of the volume are related to the peripheral beams. But this is not always the case. Some manufacturers do use a detector aligned with the X-ray source, in which the central beam is aligned with the central part of the detector and with the midplane of the FOV. This results in basis images, in which the entire FOV is seen in all images. In a 15×13 cm FOV for example, the detector must have dimensions larger than those, considering the divergence of the X-ray beam and the distance between the patient and the detector.¹² There are limiting factors, however, mostly related to the costs of the unit, and the image detector is not always large enough to fit the entire FOV, both in width and height.⁶

Two methods have been developed to obtain a FOV that is actually larger than the detector. One is volume stitching,^{2,13} in which multiple cylindrical volumes are acquired, reconstructed, and then stitched together, and the other is the use of lateral-offset detectors.^{1,6} In the latter method, during the acquisition of the basis images, the detector is horizontally offset, and not centrally aligned with the FOV (Figure 1). Only the central part

of the FOV is present in all basis images, and this area is used by the algorithm to blend the images during reconstruction, while the peripheral regions of the FOV are present in just some projections.⁶ When a lateral-offset detector is used, the resulting volume is a single cylinder, not based on stitched volumes.

The aim of the present study was to assess the effect of CBCT detector position (aligned or lateral-offset) on image technical parameters: the mean voxel value (MVV) and the standard deviation of the voxel value distribution (SDVV) by comparing peripheral regions-of-interest (ROIs) to the central ROI in the CBCT volume.

Methods and materials

Phantom

A cylindrical phantom developed and described in a previous study⁸ was used. The phantom (depicted in Figure 2) was made of utility wax, and had 98 mm in diameter, a height of 50 mm, and a cylindrical metal alloy (aluminium–copper) sample (5 mm in diameter and 5 mm in height) at the centre.

Image acquisition

Six CBCT units were used: Cranex 3Dx (CRA, Soredex Oy, Finland), Ortophos SL (ORT, Sirona Dental Systems GmbH, Germany), Picasso Trio (PIC, Vatech, South Korea), Promax 3D Mid (PRO, Planmeca Oy, Finland), Scanora 3D (SCA, Soredex Oy, Finland), and X1 (3Shape, Denmark). Eight image-acquisition protocols were selected, providing four protocols with an aligned detector, and four with a lateral-offset detector. CRA and PRO were able to acquire both aligned and

Figure 1 Schematic representation of aligned (a) and offset (b,c) detector set-ups, and a cylindrical phantom centralized in the FOV. In (a), the central X-ray beam passes through the centre of the FOV and hits the central part of the detector. In (b), it does not pass the centre of the FOV, but still hits the central part of the detector. In (c), it passes the centre of the FOV, but hits the edge of the detector. FOV, field of view.

Figure 2 Utility wax phantom used to acquire the volumes.

lateral-offset setups. Image protocols are presented in Table 1.

To acquire the images, the phantom was positioned centrally in the FOV, and the position was not changed between acquisitions. If available in the unit, tools for metal artefact correction were deactivated. The X1 required the use of the motion tracking device,^{14,15} and therefore it was set-up above the phantom and the X-ray beam trajectory. The motion correction tool was active in X1, since it was a requirement for image acquisition.

For each unit and for each protocol, five image volumes were acquired. The basis images of each acquisition were obtained to confirm the central position of the phantom within the FOV and the position of the detector in relation to the FOV (Figure 3).

Data management

The acquired CBCT volumes were exported as “digital imaging and communications in medicine” (DICOM) multfiles. The volumes were imported into dedicated software (ImageJ 1.52e, National Institutes of Health, Bethesda, Maryland, USA). Using the dedicated software, three axial sections of each volume were selected,

with the thickness defined according to the voxel size for each unit. The central axial section of the metal cylinder included in the phantom was used for ROI determination, and two sections, one 5 mm above (“upper”) and one 5 mm below (“lower”) the metal cylinder, were selected for further evaluation.

To select the ROIs for evaluation, in the central axial section (Figure 4a) showing the metal sample, a central quadrangular ROI (6 × 6 mm) was drawn centralized over the metal sample, also using the dedicated image software (Figure 4a). Based on this central ROI, 12 peripheral ROIs were defined in four directions around the metal sample (left, right, anterior, and posterior) and in three distances from the central ROI (touching the central ROI—Near; 15 mm from the central ROI—Middle; and 30 mm from the central ROI—Far) to be used in the upper (Figure 4b) and lower (Figure 4c) axial sections. The coordinates of the central ROI and the voxel size of each volume were used to calculate the coordinates of the peripheral ROIs in the upper and lower sections, which were imported into the “ROI Manager tool” in the dedicated image software. The ROIs were named laterolateral (LL, the ROIs on each side of the central) and anteroposterior (AP, the ROIs either in the front or the back of the central) samples (Figure 4b and c).

The MVV and the SDVV distribution for each ROI was measured in the “upper” and the “lower” sections. The values in the upper and lower sections were then grouped according to each of the seven regions for each unit: LL - Far, LL - Middle, LL - Near, Central, AP - Near, AP - Middle, and AP - Far. For each of these 7 groups, there were 20 values [e.g. 2 LL-Far ROIs × two sections (upper + lower) × five volumes] per unit, while there were 10 values for the central (1 ROI x 2 sections x 5 volumes). The MVV and SDVV were used for statistical comparison between the peripheral ROIs and the central ROI (*i.e.*, reference region) using ANOVA one-way with Dunnet test as *post-hoc* ($\alpha = 5\%$).

To obtain a graphical overview of the differences in MVV between the central ROI and the peripheral ROIs, MVVD was calculated as the difference of the MVV of each peripheral ROI subtracted from the MVV of the central ROI, and then divided by the MVV of the central ROI. This value was then multiplied by 100, to

Table 1 CBCT units and protocols used for volume acquisition

Name	Field of view (cm)	Detector position (offset type)	Voxel size (mm)	kVp	mA
Cranex 3Dx (CRA)	8 × 8	Aligned	0.20	89.8	6.0
Cranex 3Dx (CRA)	15 × 8	Lateral-offset (two rotations)	0.25	89.8	5.0
Orthophos SL (ORT)	11 × 10	Aligned	0.16	85.0	6.0
Picasso Trio (PIC)	12 × 8.5	Lateral-offset (360°)	0.20	80.0	3.7
ProMax 3D Mid (PRO)	10 × 10	Aligned	0.15	90.0	10.0
ProMax 3D Mid (PRO)	16 × 10	Lateral-offset (360°)	0.20	90.0	10.0
Scanora 3D (SCA)	10 × 8	Lateral-offset (360°)	0.30	90.0	13.0
X1	8 × 8	Aligned	0.15	90.0	12.0

Figure 3 Single basis image of each protocol to show the alignment or lateral-offset of images acquired before the reconstruction.

represent a percentage of increase or decrease of the value obtained in the central ROI. This parameter was selected and adapted from the SEDENTEX-CT guidelines,¹⁶ in which it is suggested that an action should be taken when image density values present a higher than 10% difference between multiple acquisitions of the same volume. The statistical analysis and the graphics depicting SDVV and MVVD values were performed using Prism 7.05 (GraphPad Software, La Jolla, CA).

Results

The average and range of the 20 MVVs for all peripheral ROIs are presented in Table 2. The central ROI showed, for all units and protocols, a relatively large range of MVVs. In the units with aligned detectors, the MVV for ORT increased, and CRA and X1 decreased, in both AP- and LL-Far regions with statistically significant differences compared to the central region ($p < 0.01$). For PRO, a significant increase was observed only for the LL-Far region ($p < 0.01$). In the units with lateral-offset detectors, a significantly increased MVV was found for CRA in AP- and LL-Far ($p < 0.01$), for PIC in LL-Middle ($p = 0.02$), AP-Middle ($p = 0.03$) and

both Far regions ($p < 0.01$), and for PRO for all regions ($p < 0.01$). No statistically significant difference was observed in the mean voxel values between the central ROI and any peripheral ROI for SCA.

SDVV for aligned detectors was lower in the ROIs near the centre, except for PRO. For the units with offset detectors, SDVV was lower for the ROIs farther from the centre, except for PIC. For the aligned detectors, SDVV showed statistically significant differences compared to the central ROI in all ROIs for CRA ($p < 0.01$), and in AP- and LL-Far for ORT ($p < 0.01$ for both) and PRO ($p < 0.01$ and $p = 0.04$, respectively). In the protocols with lateral-offset detectors, statistically significant differences were seen for AP- and LL-Far for PIC ($p < 0.01$) and PRO ($p < 0.01$), and in all ROIs for SCA ($p < 0.01$).

SDVV and MVVD for aligned and lateral-offset detectors are presented in Figures 5 and 6. MVVD observed for units with aligned detectors ranged from -32.8 to 22.8% , while for the units with lateral-offset detectors it ranged from -20.7 to 69.5% . For the units with aligned detectors, the ROIs, which were farther from the central region, were those with the largest MVVD. For units with lateral-offset detectors the same was seen for CRA and PIC, but not for PRO and SCA.

Figure 4 Axial sections of Picasso Trio (PIC) images in the centre of the metal sample used for ROI selection (a), and above (*i.e.* upper) (b) and below (*i.e.* lower) (c) the metal sample used for evaluation of 12 peripheral ROIs. ROI, region of interest.

Table 2 Average and range of MVV obtained in the seven ROIs in all CBCT units

Unit – FOV (cm)	ROI–MVV (range)						
	LL-Far	LL-Middle	LL-Near	Central	AP-Near	AP-Middle	AP-Far
<i>Aligned detector</i>							
CRA - 8 × 8	50.7 (45.9–56.3)	80.1 (76.7–83.1)	75.9 (70.5–81.4)	74.7 (70.6–79.1)	72.3 (65.2–77.2)	79.7 (64.3–93.8)	50.2 (29.3–70.2)
ORT - 11 × 10	–187.5 (–235.5––122.3)	–231.5 (–249.8––208.2)	–242.2 (–258.6––227.9)	–233.3 (–243.0––224.1)	–241.1 (–250.8––230.8)	–231.5 (–240.6––215.1)	–180.0 (–193.4––155.7)
PRO - 10 × 10	–123.9 (–130.1––116.5)	–129.1 (–133.0––124.6)	–129.1 (–131.6––125.5)	–130.1 (–132.2––127.6)	–130.9 (–136.7––126.4)	–130.0 (–134.3––124.2)	–127.3 (–138.8––120.7)
X1 - 8 × 8	457.10 (341.5–603.4)	619.2 (550.3–699.9)	668.7 (585.2–747.4)	673.9 (601.4–747.1)	661.3 (585.5–739.9)	627.0 (550.9–724.8)	478.00 (372.1–647.5)
<i>Lateral-offset detector</i>							
CRA - 15 × 8	–13.7 (–16.2––12.0)	–49.1 (–53.1––42.6)	–53.4 (–66.0––40.5)	–44.9 (–47.4––42.4)	–54.3 (–63.1––45.0)	–49.4 (–70.9––26.7)	–14.9 (–50.9–21.9)
PIC - 12 × 8.5	–122.6 (–142.3––104.6)	–165.5 (–192.3––138.6)	–193.7 (–231.8––153.6)	–182.9 (–198.5––167.9)	–191.1 (–204.9––178.4)	–165.8 (–183.9––151.4)	–124.8 (–142.6––108.3)
PRO - 16 × 10	–110.5 (–114.5––103.3)	–104.0 (–107.9––100.6)	–112.1 (–116.4––108.5)	–118.3 (–125.9––114.1)	–112.9 (–117.9––106.7)	–103.7 (–110.6––99.4)	–110.1 (–118.8––102.2)
SCA - 10 × 8	–161.4 (–184.2––142.5)	–141.8 (–163.6––127.3)	–156.9 (–196.3––131.9)	–147.0 (–167.7––103.7)	–134.6 (–171.7––68.4)	–135.5 (–170.9––101.7)	–143.4 (–186.5––105.5)

AP, anteroposterior; FOV, field of view; LL, laterolateral; MVV, mean voxel value; ROI, region of interest.

Discussion

This study focused on presenting a feature that some dental CBCT units use to acquire volumes, which are larger in diameter than the imaging detector used: changing the location of the centre, allowing it to be laterally offset from the midplane of the FOV. The use of a laterally positioned detector in dental CBCT units can be implemented in two manners.^{1,4,6} In some units, the detector is always offset to the same side, and a full rotation (*i.e.* 360°) around the patient is needed. Some units with this trajectory are the Picasso Trio (Vatech, South Korea) and Scanora 3D (Soredex Oy, Finland) for all FOV sizes, and Promax 3D Mid (Planmeca Oy, Finland) for larger FOVs. We now present a second variation in dental CBCT units, used by some manufacturers, where the machine does a first clockwise partial rotation (180° + the beam angle)² with the detector offset to one side, then the entire C-arm (with the X-ray source and the detector) moves leaving the detector offset to

the opposite side, and rotates back counterclockwise to the initial position. Some units with this trajectory are the Cranex 3Dx (Soredex Oy, Finland) and the OP300 Maxio (Instrumentarium Dental, Finland) in larger FOVs. We analyzed images of a utility wax phantom to evaluate some technical parameters among different units (*i.e.* mean voxel value and standard deviation of voxel value distribution within an image volume).

A detector with a lateral-offset position might affect the resulting image as the number of projections available for reconstructing an image is different depending on the ROI covered in each offset acquisition. In other words, the central region of the FOV is covered during the full examination, while peripheral regions are present only in some basis images during some specific periods of the partial rotations. Therefore, the number of projections available for reconstruction is different among different regions of the volume. The central cylindrical part of the volume is seen in all projections to be able to blend the projections before reconstruction, essentially almost

Figure 5 SDVV distribution in the central and peripheral ROIs for imaging protocols based on aligned and lateral-offset detectors. The lines between the dots are presented merely to follow the ROIs of the specific units. ROI, region of interest; SDVV, standard deviation of voxel value.

Figure 6 MVVD for imaging protocols based on aligned and lateral-offset detectors. The central ROI was used as the reference for the other regions and therefore is presented as zero in this comparison. The lines between the dots are presented merely to follow the ROIs of the specific units. MVVD, mean voxel value difference; ROI, region of interest.

doubling the number of images of this region compared to the others, in both types of laterally offset detectors. The area between these two parts can show ring artefacts in the reconstructed images.⁶

Adding to that, the central X-ray beam may be aligned with the centre of the detector, and not with the centre of the FOV. Therefore, using laterally offset detectors, the midplane of the projections, the region where the central (and most perpendicular) X-ray beam hits the detector, might not represent the midplane of the reconstructed volume. Also, it is accepted that technical parameters related to the overall image quality (*i.e.* noise and resolution) of any region within the FOV may be hampered when farther away from the central plane (*i.e.* image quality degrades as a function to the distance from the central plane of the FOV).^{5,17}

The central region of the tested phantom was used as reference for statistical comparisons and for MVVD calculation based on the assumption that it corresponds to the midplane section, where the photons hit the detector perpendicularly, and therefore should present more homogeneous values than regions farther from it.^{4,11} At least for SDVV, which in this study was used as a method to evaluate the homogeneity of the image,¹⁸ it is expected that the central region presents lower values than the others due to the more acute cone angles in other regions.

These two changes related to laterally offset detectors (the different number of projections within regions of the FOV, and the offset of the central beam in relation to the midplane of the FOV), were observed for the units CRA 15 × 8 and PRO 16 × 10. The ROI, which was farther from the FOV centre, had lower SDVV values than those of ROI near the centre, while the central region, that had more projections available for reconstruction, had a SDVV lower than those of ROIs near the centre. This can be explained by the fact that the entire C-arm moves to the side when acquiring images with the lateral-offset detector in these units, therefore it is understandable that the central beam is still aligned with the central area of the detector, which is not centrally aligned to the FOV. Although only PRO 16 × 10 presented statistically significant differences in the aforementioned ROI, it

is important to note the change in SDVV distribution observed between aligned and laterally offset detector positions for CRA, where the CRA 8 × 8 protocol presented statistically significant higher SDVV for the ROI far from the centre.

The other units with an aligned detector setup also had the highest SDVV for the ROIs farther from the centre, except for PRO 10 × 10. This behaviour was also observed for PIC that has a lateral-offset detector, but a standard deviation in the evaluated ROIs that resembles the ones observed in the aligned detector units. One can speculate that, even though the detector is offset for all FOVs, the central beam is aligned with the edge of the detector, making it aligned with the midplane of the reconstructed volume as well. It is important to highlight that other parameters of the units, defined exclusively by the manufacturers, could have influenced the present results. As examples, one could mention the location of the centre of rotation, the detector dimensions, and the acquisition time/number of projections. As these parameters are not controllable by the user in most cases, the methods used in the present study were executed in a way to evaluate the influence of the projection geometry alone, as selectively as possible.

Different studies have evaluated the variations in mean pixel intensities and noise in different positions of an object inside the FOV.^{7–10} Oliveira *et al*⁷ observed variations in CT values in ROIs located in different tooth regions using a NewTom 3G and 5G with different FOVs. No information was provided on the geometry of projections. Molteni⁴ listed the NewTom VGi as a unit that has an lateral-offset detector, but this information is not necessarily true regarding subsequent units by this brand. Our results showed diverse MVVD distributions comparing aligned and offset detectors. These results show that MVVD alone cannot be used to define which type of projection geometry was used. Some of the MVVDs observed in our study were higher than the 10% suggested by SEDENTEXCT,¹⁶ when considering the variation in image density values compared to a baseline image. Interesting to notice, the differences found in the present study are higher than what has been defined as acceptable.

The results found by Machado *et al*¹⁰ evaluating artefact formation in implants, using the standard deviation of the voxel value distribution, are consistent with the ones of the present study for most aligned detectors, if considered that the anterior region is usually closer to the edges of the FOV than the posterior regions in dental scans.⁹ No information was given on the projection geometry, but the device has a 20 × 25 cm amorphous silicon flat panel detector,¹⁹ large enough to cover in all projections in the entire FOVs. Another study⁸ observed results similar to ours for PIC, even though different methods of positioning the phantom were used. Higher SDVVs were observed around the metal object when closer to the edge of the phantom. One of the studies also evaluated the basis images.⁹ The aligned detector of the unit used in the study presented similar SDVV increase in the edges of the FOV as observed in our study for aligned detectors.

Further studies should focus on the influence of these different image acquisition geometries on different diagnostic tasks. Emphasis must be on explaining how the patient would be affected by the variation highlighted in the present study, considering both the diagnostic

outcome and the radiation burden to the patient in these projections.

Conclusion

MVV in peripheral ROIs varied considerably and varied more from the central ROI, the farther from the central ROI, in all projection geometries. Lateral-offset detectors to acquire CBCT images significantly changed SDVV distribution within the FOV, and led to MVVD with increased range, compared to aligned detectors. These findings must be taken in consideration in the clinic, if voxel value dependent measurements are to be performed.

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