RESEARCH ARTICLE

Standardized method to quantify the variation in voxel value distribution in patient-simulated CBCT data sets

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Objectives: To suggest a standardized method to assess the variation in voxel value distribution in patient-simulated CBCT data sets and the effect of time between exposures (TBE). Additionally, a measurement of reproducibility, Aarhus measurement of reproducibility (AMORE), is introduced, which could be used for quality assurance purposes.

Methods: Six CBCT units were tested [Cranex[®] 3D/CRAN (Soredex Oy, Tuusula, Finland); Scanora[®] 3D/SCAN (Soredex Oy); NewTom[™] 5G/NEW5 (QR srl, Verona, Italy); i-CAT/ICAT (Imaging Sciences International, Hatfield, PA); 3D Accuitomo FPD80/ACCU (Morita, Kyoto, Japan); and NewTom VG/NEWV (QR srl)]. Two sets of volumetric data of a wax-embedded dry human skull (containing a titanium implant) were acquired by each CBCT unit at two sessions on separate days. Each session consisted 21 exposures: 1 “initial” followed by a 30-min interval (initial data set), 10 acquired with 30-min TBE (data sets 1–10) and 10 acquired with 15-min TBE (data sets 11–20). CBCT data were exported as digital imaging and communications in medicine files and converted to text files containing *x*, *y* and *z* positions and grey shade for each voxel. Subtractions were performed voxel-by-voxel in two set-ups: (1) between two consecutive data sets and (2) between any subsequent data set and data set 1. The mean grey shade variation for each voxel was calculated for each unit/session.

Results: The largest mean grey shade variation was found in the subtraction set-up 2 (27–447 shades of grey, depending on the unit). Considering subtraction set-up 1, the highest variation was seen for NEW5, between data sets 1 and the initial.

Conclusions: Discrepancies in voxel value distribution were found by comparing the initial examination of the day with the subsequent examinations. TBE had no predictable effect on the variation of CBCT-derived voxel values. AMORE ranged between 0 and 64.

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Keywords: cone beam CT; voxel value; grey shade distribution

Introduction

The presence of artefacts^{1–3} and the inconsistency of the voxel values composing an image^{4–7} are some of the major drawbacks related to CBCT data sets. Although there are studies dealing with this innate (and apparently non-avoidable) voxel value variation related to

CBCT-generated images, these have mainly focused on reporting signal-to-noise and contrast-to-noise ratios.^{8,9} A few studies assessed the unsuitability of using CBCT-derived voxel values to derive Hounsfield units for bone density estimation but with no further explanation on the origin or the magnitude of the problem was given.^{10–12}

Only a few recent studies attempted to quantify and/or explain the grey shade variation in CBCT data sets.^{5,6,13,14} The most recent one showed a mean variation

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Table 1 Data acquisition protocols

Parameter	CBCT unit					
	CRAN	SCAN	NEW5	ICAT	ACCU	NEWV
Scan time	10.1 s	13.0 s	18.0 s	26.9 s	17.5 s	18.0 s
Exposure time	2.3 s	3.0 s	3.1 s	7.0 s	17.5 s	3.6 s
Field of view	6 × 4 cm	6 × 6 cm	8 × 8 cm	8 × 8 cm	4 × 4 cm	8 × 8 cm
Tube potential	90 kV	90 kV	110 kV	120 kV	90 kV	110 kV
mA	12.5	12.5	0.65	5	5	0.65
Voxel resolution	0.20 mm	0.20 mm	0.30 mm	0.25 mm	0.08 mm	0.30 mm
Nominal bit depth (bits)	12	12	16	14	13	16

ACCU, 3D Accuitomo FPD80 (Morita, Kyoto, Japan); CRAN, Cranex[®] 3D (Soredex Oy, Tuusula, Finland); ICAT, i-CAT (Imaging Sciences International, Hatfield, PA); NEW5, NewTom[™] 5G (QR srl, Verona, Italy); NEWV, NewTom VG (QR srl); SCAN, Scanora[®] 3D (Soredex Oy).

up to 165 shades of grey for 6 highly acknowledged CBCT units.⁶ Apparently, the pattern of the variation differed for some units depending on the time interval between exposures (30 min *vs* no interval).⁶

Voxel value variation should be considered when defining quality assurance protocols. This should be carried out “in a way so that users can assess whether their unit is operating consistently and are inline with the expectation for these types of units”.¹⁵ The latest European guidelines suggest that voxel values of a “baseline image” could be compared with values measured in subsequent examinations as a method to assess the stability of a unit in providing constant values for identical structures.¹⁵ An “image density value” variation of 10% is suggested as the threshold for acceptable voxel value reproducibility, although no standardized definition on how this value should be assessed is given.¹⁵

The aim of the present study was to suggest a standardized method to assess the variation in voxel value distribution in patient-simulated CBCT data sets and the effect of time between exposures (TBE). Additionally, a measurement of reproducibility, Aarhus measurement of reproducibility (AMORE), is introduced, which could be used for quality assurance purposes.

Methods and materials

Acquisition of the volumetric data sets

Six CBCT units were tested: Cranex[®] 3D (CRAN) (Soredex Oy, Tuusula, Finland); Scanora[®] 3D (SCAN) (Soredex Oy); NewTom[™] 5G (NEW5) (QR srl, Verona, Italy); i-CAT “first generation” (ICAT) (Imaging Sciences International, Hatfield, PA); 3D Accuitomo FPD80 (ACCU) (Morita, Kyoto, Japan); and NewTom VG (NEWV) (QR srl). As a standard, the smallest possible field of view (FOV) with standard resolution was selected

for each unit. The data acquisition protocol used for each CBCT unit is shown in Table 1. Immediately after data acquisition, the data sets were exported as uncompressed digital imaging and communications in medicine multi-files,¹⁶ as previously described.⁶

Session logistics

CBCT units were tested in two sessions. The units were idle for a period of at least 12 h before the start of a session. Each session consisted 21 exposures: 1 initial exposure (initial data set) followed by a 30-min interval, 10 exposures acquired with 30-min TBE (data sets 1–10) and 10 acquired with 15-min TBE (data sets 11–20), as shown in Figure 1. The sessions took place on separate days. A dry human skull embedded in wax and containing a titanium implant served as the study object, simulating an everyday clinical set-up (patient) and assuring that a wide part of the unit’s bit-depth range (grey shade scale) would be used (*e.g.* air, soft-tissue simulation, bone and metal). To avoid minor movements of the skull, the unit’s own chair was not used for positioning the skull unless its control was isolated from the CBCT unit (NEW5 and NEWV).⁶ The skull was removed between sessions, and it was repositioned in the same manner for the next session. After an exposure session had started, the skull was not touched.

Data management

CBCT data sets were exported as digital imaging and communications in medicine multifiles and converted to text files, which were reorganized to contain *x*, *y* and *z* positions and grey shade for each voxel.⁶ The files were merged (SPSS[®] v. 13.0; Apache Software Foundation, Forest Hill, MD) to contain 1 record per voxel position, including the voxel values from the 21 exposures in a session. Subtractions voxel-by-voxel were performed in two set-ups: (1) between two consecutive data sets in a session

Figure 1 Session workflow: each session consisted 21 exposures: 1 “initial” followed by a 30-min interval (initial data set), 10 acquired with 30-min time between exposures (TBE) (data sets 1–10), and 10 acquired with 15-min TBE (data sets 11–20).

Table 2 Mean grey shade difference, mean grey shade difference in absolute numbers and the percentage of voxels that changed value inside the image cylinder (considering subtraction set-up 1, excluding the initial data set) according to unit

Unit	First session (ranges)			Second session (ranges)		
	Mean grey shade difference	Mean grey shade difference (range of absolute numbers)	Voxels that changed value (% inside the cylinder)	Mean grey shade difference	Mean grey shade difference (range of absolute numbers)	Voxels that changed value (% inside the cylinder)
CRAN	−0.5 to 0.9	30.7–49.1	79.5–80.2	−0.6 to 0.9	30.9–58.2	80.7–81.5
SCAN	−0.2 to 1.2	16.6–19.5	40.9–41.9	−0.3 to 0.5	16.5–17.7	41.2–42.0
NEW5	−2.1 to 1.7	35.6–61.6	96.9–97.0	−2.2 to 7.8	34.7–40.9	96.8–97.3
ICAT	−0.3 to 150.0	8.8–446.0	19.8–48.4	−0.6 to 37.7	14.5–481.0	35.1–51.0
ACCU	−1.3 to 1.0	33.3–64.6	98.9–99.4	−0.9 to 1.3	33.1–44.8	99.2–99.6
NEWV	−2.9 to 2.1	17.4–21.9	90.6–92.9	−1.9 to 1.2	16.5–21.5	90.1–92.3

ACCU, 3D Accuitomo FPD80 (Morita, Kyoto, Japan); CRAN, Cranex[®] 3D (Soredex Oy, Tuusula, Finland); ICAT, i-CAT (Imaging Sciences International, Hatfield, PA); NEW5, NewTom[™] 5G (QR srl, Verona, Italy); NEWV, NewTom VG (QR srl); SCAN, Scanora[®] 3D (Soredex Oy).

(data set 1 minus the initial data set, data set 2 minus data set 1, data set 3 minus data set 2 etc.) and (2) between any subsequent data set and data set 1 of that session (data set 2 minus data set 1, data set 3 minus data set 1, data set 4 minus data set 1 etc.), excluding the initial data set.

Data treatment

Commercially available software (SPSS v. 13.0) was used for data evaluation. As only two sessions for each CBCT unit were performed, only descriptive statistics of the acquired data are presented. The mean grey shade variation for each voxel in the subtraction data sets was calculated for each unit and session in absolute values.

The percentage of voxels, which changed value, was moreover calculated considering separate voxels, which were inside, outside and on the interface between the image cylinder (FOV) and corners of the volume. A “measurement of reproducibility”, named AMORE was defined as the integer percentage of voxels inside the image

cylinder that did not change value. This calculation was based on the data from subtraction set-up 2 (between any subsequent data set and data set 1 of that session).

Results

For all tested units, variation in voxel values was observed throughout the 21 exposures. Considering subtraction set-up 1 (Table 2), the mean grey shade difference observed for all units was relatively small. The largest differences between voxel values were found for ICAT (maximum variation in absolute numbers of 481 shades of grey), but these still represent <3% of variation (considering the bit depth of the unit). From the plot of the mean grey shade differences among the subtractions (Figure 2), it seems that for SCAN (first session), NEW5, ICAT and NEWV (second session), the initial examination of the day differed significantly from subsequent

Figure 2 Mean grey shade difference considering subtraction set-up 1, according to the unit. ACCU, 3D Accuitomo FPD80 (Morita, Kyoto, Japan); CRAN, Cranex[®] 3D (Soredex Oy, Tuusula, Finland); ICAT, i-CAT (Imaging Sciences International, Hatfield, PA); NEW5, NewTom[™] 5G (QR srl, Verona, Italy); NEWV, NewTom VG (QR srl); SCAN, Scanora[®] 3D (Soredex Oy).

Table 3 Mean grey shade difference, mean grey shade difference in absolute numbers and the percentage of voxels that changed value inside the image cylinder (considering subtraction set-up 2) according to unit

Unit	First session (ranges)			Second session (ranges)		
	Mean grey shade difference	Mean grey shade difference (range of absolute numbers)	Voxels that changed value (% inside the cylinder)	Mean grey shade difference	Mean grey shade difference (range of absolute numbers)	Voxels that changed value (% inside the cylinder)
CRAN	0.9 to 3.4	31.4–46.1	79.9–80.3	0.9 to 3.4	39.1–74.9	81.2–81.2
SCAN	1.2 to 2.9	19.5–32.1	41.9–44.3	0 to 1.7	17.0–22.6	41.6–42.9
NEW5	–1.6 to 7.6	61.6–171.5	96.9–97.6	–1.0 to 8.0	40.6–61.7	97.1–97.3
ICAT	0.1 to 152.0	24.2–447.0	39.4–48.6	–0.2 to 37.7	16.2–480.9	35.1–51.1
ACCU	–2.0 to 1.7	64.6–167.1	99.2–99.6	–0.9 to 0.9	40.5–52.1	99.0–99.1
NEWV	–3.9 to 2.5	18.8–27.3	90.9–92.4	–4.7 to –0.3	19.6–24.7	89.9–91.8

ACCU, 3D Accutomo FPD80 (Morita, Kyoto, Japan); CRAN, Cranex® 3D (Soredex Oy, Tuusula, Finland); ICAT, i-CAT (Imaging Sciences International, Hatfield, PA); NEW5, NewTom™ 5G (QR srl, Verona, Italy); NEWV, NewTom VG (QR srl); SCAN, Scanora® 3D (Soredex Oy).

examinations. For ICAT, two of the subtractions (one from each session) showed extremely outlying mean grey shades (Figure 2, abruption of dotted line for ICAT). The units showed similar results for both sessions. Excluding the initial examination of the day, TBE seemed to have no predictable effect on the variation of CBCT-derived voxel values.

Considering subtraction set-up 2 (Table 3), the variation was again not >3%, considering each unit's bit depth. When comparing sessions, no “fingerprints” for grey shade variation were observed for the tested units (Figure 3). The units' behaviour was not predictable and the variation was (apparently) randomly distributed.

Regarding the percentage of voxels, which changed value, and except for NEW5, voxels changed values even outside the image cylinder (in the corners of the volume). The changes in voxel values in this area were 0.1% for CRAN and SCAN, 2.4% for ICAT, 100% for ACCU and 32.1% for NEWV. The percentage of voxels

changing value inside the image cylinder varied among units, ranging from 35.1% (ICAT) to 99.6% (ACCU). In this way, AMORE ranged from 0 (ACCU) to 64 (ICAT). These results (which are complementary numbers) are presented in Table 4.

Discussion

The innate grey shade variation present in CBCT data sets may hamper a reliable assessment of image densities (in the way that it is carried out in multislice CT). Previous studies attempted to evaluate the severity of that variation but with little or no inference on its extent.

Pauwels et al⁵ measured pre-defined averaged areas within a CBCT data set and calculated the voxel value error. The authors showed an average grey shade deviation between CBCT and multislice CT of approximately 6% of the total grey shade range of a multislice

Figure 3 Mean grey shade difference (in absolute values, considering subtraction set-up 2), according to the unit. ACCU, 3D Accutomo FPD80 (Morita, Kyoto, Japan); CRAN, Cranex® 3D (Soredex Oy, Tuusula, Finland); ICAT, i-CAT (Imaging Sciences International, Hatfield, PA); NEW5, NewTom™ 5G (QR srl, Verona, Italy); NEWV, NewTom VG (QR srl); SCAN, Scanora® 3D (Soredex Oy).

Table 4 Aarhus measurement of reproducibility (AMORE), considering the subtraction set-up 2, according to unit

Unit	First session (ranges)		Second session (ranges)	
	Voxels that changed value (% inside the cylinder)	AMORE	Voxels that changed value (% inside the cylinder)	AMORE
CRAN	79.9–80.3	19–20	81.2–81.2	18–18
SCAN	41.9–44.3	55–58	41.6–42.9	57–58
NEW5	96.9–97.6	2–3	97.1–97.3	2–2
ICAT	39.4–48.6	51–60	35.1–51.1	48–64
ACCU	99.2–99.6	0–0	99.0–99.1	0–1
NEWV	90.9–92.4	7–9	89.9–91.8	8–10

ACCU, 3D Accuitomo FPD80 (Morita, Kyoto, Japan); CRAN, Cranex[®] 3D (Soredex Oy, Tuusula, Finland); ICAT, i-CAT (Imaging Sciences International, Hatfield, PA); NEW5, NewTom[™] 5G (QR srl, Verona, Italy); NEWV, NewTom VG (QR srl); SCAN, Scanora[®] 3D (Soredex Oy).

CT. Recently, Spin-Neto *et al*⁶ reported a variation up to 165 shades of grey in a series of CBCT data sets acquired in widely used units. In the same study, it was suggested that the pattern of the variation differs depending on the time interval between exposures, based on calculations made at the voxel level, considering the full volume of interest.⁶

Defining how to assess the voxel value variation is important when considering the implementation of quality assurance protocols. Current guidelines recommend assessing image density value variation and noise, monthly and yearly, respectively, although this is not cited as essential for the quality assurance protocol.¹⁵ The same guidelines suggest a threshold of 10% as the trigger for taking action (further investigation and service engineer support) towards the problem.¹⁵ Guidelines are rather broad and lack standardization on how to determine voxel value variation: it is suggested that a “baseline image” should be compared with subsequent examinations, and that the voxel values for similar structures must be measured.¹⁵ No further explanation on how to proceed is given.

In the present study, our intention was to suggest a standardized method to assess the variation in voxel value distribution in patient-simulated CBCT data sets. This method could be used as a part of a quality assurance protocol. Care was taken to maintain the fixed position of the object of interest (skull) during the sessions. This guaranteed that small inconsistencies in the positioning of the unit’s chair from one exposure to another were avoided.⁶ Special attention was also given to the positioning of the region of interest (part of the skull—mandible—containing a titanium implant) inside the FOV, and also to standardize the use of the smallest possible FOV for all tested units. However, voxel value variation could not be predicted between two sessions of the same unit. Besides the simple variation between two sessions of the same unit owing to phantom-positioning variation (currently, patient-positioning devices do not allow perfect standardization through time), one could speculate that other parameters, such as electricity variation and geometric inaccuracies during image acquisition (*e.g.* variation in the starting point of the unit’s arm and rotation speed) could be related to that finding. Although this was not considered in the present study, assessing X-ray tube output during the sessions could add relevant data to explain the voxel–value variation.

Based on the presented methodology, voxel variation in all units was always far below the suggested 10% threshold (highest variation found was close to 3% in absolute numbers). It is important to mention that there is no documented rationale for a threshold of 10%. It may be that even small variations in voxel values may influence image quality and particularly bone density estimation, but the eventual impact of the variation on the diagnostic outcome is still to be studied.^{2,6}

We further assessed the influence of TBE on the voxel value variation. The present results suggest that for most units, TBE seems to have no predictable effect on the variation of CBCT-derived voxel values. For most of the units, the initial examination of the day differed substantially from subsequent examinations, suggesting that these units need an extra “warm up” before the optimal voxel value stability can be achieved.

To quantify the extent to which voxel value variation affects a data set, we separated the voxels that were inside and outside the image cylinder. A previous study from our group showed the percentage of voxels that changed value ranged from 55% to 99%, depending on the CBCT unit.⁶ But in that study, there was no differentiation between what was inside and outside the image cylinder. In the present study, except for NEW5, voxels changed values even outside the image cylinder (ranging from 0.1% for CRAN and SCAN, to 100% for ACCU). This is a remarkable finding, since one should expect that the reconstruction algorithms would be able to identify what is part of the actual image and what is not. Inside the image cylinder, the percentage of voxels changing value ranged from 35.1% (ICAT) to 99.6% (ACCU). Three main factors could be related to this wide range: FOV size (according to what is called the “local tomography effect”),^{17,18} resolution (voxel size) and bit depth (number of grey shades). Two studies in literature suggested the influence of FOV size on the trabecular bone microstructural measurements obtained from CBCT images, owing to the diminished voxel value accuracy related to larger FOVs and other scanning parameters.^{19,20} Owing to the characteristics of the present study design, it was not possible to make further inference on this topic.

To provide an easy referral value regarding the extent of voxel variation in a data set, we suggest a measurement of reproducibility, AMORE. A range from 0 (ACCU, *i.e.* all voxels changed value over time) to 64 (ICAT, *i.e.* almost

two-thirds of voxel values were stable over time) was found based on the current analysis. This could be used as a parameter for further quality assurance protocols, although the impact of this specific value on the diagnostic capacity of CBCT images needs to be further investigated.

One could speculate on the differences in AMORE for the tested units, suggesting the same factors already addressed (FOV size, resolution and bit depth) as an explanation for those differences. As can be seen from our results, the two lowest AMORE scores were found for ACCU and NEW5, which are units that differ considerably regarding those parameters. Determining which factor(s) would be dominant on the definition of the reproducibility values was not possible.

In the present study, we attempted to describe a standardized methodology to generate, export and evaluate CBCT data sets regarding the stability of the voxel values in the images. Our main idea was to provide a robust methodology, which could be used as routine in imaging clinics. Nevertheless, our results must be interpreted with care, since just one unit of each type was tested and, therefore, it would not be just to compare the various CBCT unit brands statistically.

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Conclusion

Our results showed that discrepancies in CBCT voxel value distribution are seen when comparing the initial examination of the day with subsequent examinations. Excluding the initial examination of the day, TBE has no predictable effect on the variation of CBCT-derived voxel values. AMORE ranged between 0 and 64. The sources of the voxel value variation must be further studied.

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