RESEARCH ARTICLE

Influence of exposure factors on the variability of CBCT voxel values: a phantom study

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Objectives: To assess the influence of milliamperage and kilovolt peak (kVp) on the variability of cone beam CT (CBCT) voxel values.

Methods: CBCT scans were obtained from radiographic phantoms in varying concentrations of dipotassium hydrogen phosphate solutions ($200\text{--}1200\text{ mg ml}^{-1}$) under different protocols of milliamperage and kVp. In addition, scans were performed with and without a dental implant and exo-mass. The variability of CBCT voxel values was measured on each scan, and factorial analysis of variance and the *post hoc* Tukey test were performed ($\alpha = 0.05$). Linear regression was performed to assess the relationship between voxel value variability and dipotassium hydrogen phosphate concentration.

Results: milliamperage and the presence of a dental implant did not produce significant interference ($p = 0.28$ and 0.87 , respectively) in voxel value variability. Scans at the highest kVp value presented a significant reduction ($p \leq 0.0001$) in voxel value variability when only exo-mass was not present. Voxel value variability was not influenced by exo-mass in scans at the highest levels of milliamperage and kVp. The presence of exo-mass produced a significant reduction ($p \leq 0.0001$) in voxel value variability in most of the scans. Higher concentrations yielded greater variations in voxel values in all scans, except for those operating at the highest levels of mAs and kVp.

Conclusions: mAs did not influence the variability of CBCT voxel values; higher kVp reduced such variability when only the object was smaller than the field of view.

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Introduction

Cone beam CT (CBCT) is an imaging modality with increasing application in dentistry, considering its positive diagnostic outcomes. Similar to fan beam CT (FBCT), which is more frequently used in medical fields, CBCT allows for a three-dimensional interpretation of structures with high spatial resolution.¹ Several studies have indicated CBCT as the imaging modality of choice in

oral implantology.² Information about the quantity and quality of the alveolar bone is of fundamental importance for dental implant treatment planning. Bone height and thickness can be obtained from CBCT images with sub-millimetre accuracy. Conversely, it is not advisable to perform bone quality analysis on such images.^{1,3}

A CT image is built on a matrix of voxels that individually display a shade of grey in a scale from black to white and are related to the linear attenuation coefficient of the scanned structure. On FBCT, the voxel value reliably represents the physical properties of the structures, such as density, by means of Hounsfield

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units.⁴ However, CBCT has been shown to be inaccurate for this task because of the inhomogeneity of the voxel values. Among the many reasons presented in the scientific literature to explain this, the increased production of X-ray noise owing to the large coverage of the cone-shaped beam and its interaction with the image receptor, which is flat and wide, must be highlighted.^{1,5} These contribute to the degradation of the resultant image with decreased contrast resolution and image noise formation (grainy aspect) and can be determined by a relationship between the X-ray signal and noise that is known as the signal-to-noise ratio. The milliamperage is one of the factors that determine the amount of signal. Higher milliamperage values increase the signal-to-noise ratio, which yields better image quality.⁵

Another factor related to the inaccuracy of CBCT voxel values is the great susceptibility of image artefact formation. Numerous types of image artefacts have been described according to their aetiology.⁶ Some are related to X-ray beam hardening and can be visualized when objects with high atomic number are located in the field of view (FOV).⁷ The kilovolt peak (kVp) determines the quality of the X-ray beam and therefore the occurrence of beam hardening. Higher kVp values increase the energy of the beam, which becomes less susceptible to hardening.^{5,7} Some CBCT units allow the operator to adjust exposure factors, such as milliamperage and kVp, and this has a significant impact on the effective dose to the patient. However, little is known about how milliamperage and kVp influence the variability of CBCT voxel values and, consequently, the representation of physical densities on the image. Thus, the aim of this study was to assess the influence of milliamperage and kVp on the variability of CBCT voxel values.

Methods and materials

Aqueous solutions of dipotassium hydrogen phosphate (K_2HPO_4) were prepared at six concentrations (1200, 1000, 800, 600, 400 and 200 mg ml⁻¹) and stored separately in 0.2-ml polypropylene tubes. K_2HPO_4 is a salt with high water solubility and atomic number very close to that of calcium hydroxyapatite (15.58 and 15.86, respectively). This concentration range was selected to represent the alveolar bone with a broad range of mineralization.

Radiographic phantoms were custom fabricated: 28 tubes with the same concentration were placed within a container of polypropylene (diameter, 9 cm; height, 6 cm). A thin layer of wax was fixed on the inside bottom of the container, and the tubes were positioned vertically and symmetrically arranged in three circles from the centre. The inner, middle and outer circles had 4, 8 and 16 tubes, respectively. The container was filled with water to simulate soft-tissue absorption and scatter radiation.

Each phantom was centred separately in the middle of an FOV (diameter, 12 cm; height, 8.5 cm) in the

Picasso-Trio CBCT unit (Vatech/E-WOO Technology, Seoul, Republic of Korea), and four scans were performed under the following protocols: 3 mAs and 50 kVp; 9 mAs and 90 kVp; 3 mAs and 90 kVp; and 5 mAs and 50 kVp. All scans were set at a standard mode, which resulted in images with a voxel size of 0.3 cm, scanning time of 15 s and bit depth of 16 bits. Thereafter, a dental implant (Straumann®, Basel, Switzerland) was placed vertically in the centre of each phantom to stimulate the formation of beam-hardening artefacts, and all the CBCT scans were repeated. The phantoms were then placed within a bigger container (diameter, 18 cm; height, 10 cm) filled with water, and all previous scans were repeated. The bigger container was used with the intention of exceeding the volume of the FOV and simulating a clinical situation in which exo-mass is observed. Thus, a total of 16 scanning protocols (Table 1) and 96 scans were obtained, and the volumetric data were reconstructed and evaluated in the native Ez3D software package (Vatech/E-WOO Technology).

On cross-sectional slices, rectangular regions of interest (20 mm²) were selected within the tubes, and the mean CBCT voxel values were obtained. To access the variability of CBCT voxel values (voxel value variability), the standard deviation from the 28 CBCT voxel values was obtained for each phantom. After exploratory analysis of the data, factorial analysis of variance 2 × 2 × 2 × 2 (implant × exo-mass × milliamperage × kVp) for differences in the voxel value variability and the *post hoc* Tukey test were performed. The significance level was set at 5%. Linear regression was performed to assess the relationship between voxel value variability and K_2HPO_4 concentration for scans with no exo-mass.

Results

The milliamperage settings used in this study and the presence of a dental implant in the middle of the FOV

Table 1 Cone beam CT scanning protocols for different values of kilovolt peak (kVp), milliamperage and the presence of exo-mass and implant

Protocols	Implant	Exo-mass	milliamperage	kVp
1	Yes	Yes	3	50
2	Yes	Yes	3	90
3	Yes	Yes	9	50
4	Yes	Yes	9	90
5	Yes	No	3	50
6	Yes	No	3	90
7	Yes	No	9	50
8	Yes	No	9	90
9	No	Yes	3	50
10	No	Yes	3	90
11	No	Yes	9	50
12	No	Yes	9	90
13	No	No	3	50
14	No	No	3	90
15	No	No	9	50
16	No	No	9	90

did not produce significant interference ($p = 0.2822$ and 0.8688 , respectively) in voxel value variability.

Scans at 90 kVp presented significant reduction ($p \leq 0.0001$) in voxel value variability when only exo-mass was not present. Although not statistically significant, a reduction was also observed in scans with exo-mass, except for those with the dental implant and at 3 mAs (Table 2).

Voxel value variability was not influenced by the presence of exo-mass in scans at the highest levels (9 mAs and 90 kVp). The presence of exo-mass produced a significant reduction ($p \leq 0.0001$) in voxel value variability when scans were performed at 3 mAs and 50 kVp; 3 mAs and 90 kVp; and 9 mAs and 50 kVp (Table 2).

When interpreting the distribution of voxel value variability according to the concentration of K_2HPO_4 on scans that presented significant differences for kVp (scans with no exo-mass), higher concentrations yielded greater voxel value variation in scans at 3 mAs and 50 kVp; 3 mAs and 90 kVp; and 9 mAs and 50 kVp, regardless of the presence of a dental implant. Conversely, scans operating at 9 mAs and 90 kVp revealed an inversely proportional relationship between voxel value variability and K_2HPO_4 concentration (Figure 1).

Discussion

The use of CBCT images for assessing clinical density has proven to be inaccurate and unreliable owing to the inhomogeneity of CBCT voxel values.^{1,3–5} This evidence has a significant impact when information is needed about alveolar bone quality before implant placement. The fact that CBCT has important similarities to FBCT may be responsible for a misconception among some dental practitioners who consider both imaging modalities comparable with respect to density assessment.⁸ Some studies have successfully established a conversion factor between CBCT and FBCT voxel values; however, these investigators assumed that the relationship between X-ray attenuation and CBCT voxel values is uniform throughout the FOV.^{9–11} FBCT

expresses voxel values as Hounsfield units, which represent X-ray attenuation relative to the attenuation of water.⁴ Current CBCT units do not use a standard scaling system, although some studies have shown linearity between the voxel values obtained from this imaging modality and FBCT.^{3,12,13} The scientific literature has revealed many factors that are involved in this limitation of CBCT technology.^{3–5} In CBCT, the cone-shaped X-ray beam increases the amount of X-ray scattering that is captured by a flat image detector and, in addition to the use of lower exposure settings, favours image artefact formation with inadequate grey scale sensitivity to discern subtle differences between low-density tissues, such as soft tissues.^{6,14}

Given the proven inhomogeneity of CBCT voxel values, the present study aimed to assess the influence of exposure factors (milliamperage and kVp) on voxel value variability. The variability of a CBCT scan was established in this study as the standard deviation of CBCT voxel values obtained from the 28 tubes for the same phantom (the same K_2HPO_4 concentration). Higher values of standard deviation represent greater voxel value variability.

The exposure factors were at the highest and lowest possible levels (3 and 9 mAs; 50 and 90 kVp), because such variations in milliamperage and kVp dramatically interfere, respectively, with the signal-to-noise ratio and X-ray beam-hardening effect of the scans and enable us to assess their relationship with the distribution of CBCT voxel values. The CBCT unit used in this study allows for adjustments in milliamperage and kVp within a range of 2–10 mAs and 40–100 kVp, respectively. However, in a subjective analysis of a previous pilot study, the use of extreme exposure factors significantly reduced the image quality of the phantoms. Similar to Pauwels *et al*,¹⁵ who tested 13 different CBCT units, our results show that noise (low signal-to-noise ratio, in this case, set by milliamperage adjustment) did not affect the measurements of voxel value variability. However, scans at high kVp accounted for significant reduction in voxel value variability on scans with no exo-mass. This might be related to the fact that there was no attenuation and scattering of the primary X-ray beam before it reached the FOV.

Table 2 Mean values ($\pm$ standard deviation) of the voxel value variability measured for radiographic phantoms with different dipotassium hydrogen phosphate concentrations

Implant	Milliamperage	Exo-mass	Kilovolt peak	
			50	90
No	3	Yes	64.71 (19.59) Aa	49.49 (19.80) Aa
		No	340.95 (95.41) Ab	181.66 (52.24) Bb
	9	Yes	80.74 (29.67) Aa	52.73 (20.61) Aa
		No	362.61 (104.41) Ab	76.86 (34.83) Ba
Yes	3	Yes	37.10 (47.52) Aa	50.61 (18.44) Aa
		No	344.08 (96.87) Ab	184.93 (50.36) Bb
	9	Yes	80.42 (29.74) Aa	53.12 (20.46) Aa
		No	366.92 (107.02) Ab	76.75 (37.73) Ba

Mean values followed by different letters (lowercase for vertical and uppercase for horizontal) are significantly different from each other ($p \leq 0.05$).

No significant difference was observed between groups with and without an implant ($p = 0.8688$) and between groups with different milliamperages ($p = 0.2822$).

Figure 1 Relationship between voxel value variability and phantoms with different dipotassium hydrogen phosphate (K_2HPO_4) concentrations ($mg\ ml^{-1}$). These scans include phantoms with no exo-mass, with and without a dental implant, and under different values of milliamperage and kilovolt peak (kVp). The linear regression line is indicated.

In an attempt to reproduce different clinical situations, the present methodology included scans with and without a dental implant and exo-mass. Implant-based dental reconstruction has become an affordable option for patients, who frequently undergo imaging for treatment planning. It is well known that dental implants produce artefacts on imaging because they absorb low-energy X-ray photons owing to their high atomic number and increase the mean energy of the beam, a phenomenon known as beam hardening.¹⁶ This study shows that the presence of a dental implant in the FOV did not change the voxel value variability significantly. Because the radiographic phantom was filled with water, the X-ray beam might have been attenuated to the point of restricting the implant-related beam-hardening effect to the most central area, which was not very significant over the whole phantom. Subjective evaluation of the CBCT scans with no exo-mass revealed the presence of streaking artefacts arising from the dental implant (Figure 2).

Exo-mass is a term used to refer to structures that exceed the limits of the FOV.¹⁷ In dentistry, considering the size and location of the oral cavity and surrounding structures, exo-mass is present in most scans in which an

adequate FOV size is used. By contrast, exo-mass may not be present when very large FOV sizes are indicated, for example, airways and cephalometric analyses for orthognathic surgery. This study showed a reduction in voxel value variability when exo-mass was present, in contrast to Katsumata *et al*¹⁸ who suggested that larger FOVs (less exo-mass) have the advantage of better density reliability. In this *in vitro* study, because the exo-mass was a homogeneous and thin layer of water, it might have acted as an X-ray filter. This might have increased the mean energy of the X-ray beam, which became less susceptible to variations in the FOV. Such exo-mass-related differences highlight the importance of considering exo-mass when designing methodologies to evaluate CBCT voxel values.

Although not visible to the naked eye, the voxel value variability increased in most scans obtained from phantoms with higher K_2HPO_4 concentration and no exo-mass. That may be explained by the fact that phantoms at high concentrations are more susceptible to the beam-hardening effect and, consequently, to image degradation. The magnitude of such variability was inversely proportional to the K_2HPO_4 concentration on

Figure 2 Axial reconstruction of cone beam CT scans with a dental implant and no exo-mass at different exposure factors: (a) 9 mAs and 90 kVp; (b) 3 mAs and 50 kVp; (c) 9 mAs and 50 kVp; and (d) 3 mAs and 90 kVp.

scans operating at the highest levels of milliamperage and kVp. This could reveal greater homogeneity of the X-ray beam when the signal-to-noise ratio and the mean energy are high, with compensation for the occurrence of scatter radiation and beam hardening. Similarly, Hunter and McDavid¹⁹ stated that such compensation decreases CBCT voxel value variability. Emphasis should be given to the fact that the use of higher milliamperage and kVp settings increases the effective dose to the patient.

Therefore, optimal adjustment of exposure factors should be determined by the clinical objectives of the examination.

In conclusion, exposure factors, such as milliamperage and kVp at the levels used in the present study, did not influence the variability in CBCT voxel values when the object exceeded the FOV size. However, kVp reduced this variability in scans in which the FOV encompassed the entire object.

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