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Analysis of the reproducibility of the gray values and noise of a direct digital radiography system

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Abstract: The aim of this study was to evaluate the reproducibility of the gray values and noise of a direct digital radiography system (Visualix eHD) for various exposure times and analyzed regions. To obtain radiographic images in a standardized manner, the digital sensor of the system and a stepwedge were positioned in a phantom at a focus-film distance of 30 cm in a dental device at 70 kV, 7 mA and 2.2 mm filtration. Ten consecutive repetitions of X-ray imaging were performed at each exposure time (0.05, 0.07, 0.09 and 0.13 s). Gray values were analyzed using ImageJ software in five regions of interest (ROIs): alveolar bone (AB), soft tissue (ST) and three steps of the stepwedge (S1, S2 and S3). The results showed that both the variability of the gray values and the noise were statistically greater ($p < 0.05$) in the most radiolucent region (ST). Only the noise was affected by the exposure time. In conclusion, the reproducibility of the gray values and the noise of the Visualix eHD system can vary in specific areas with different radiolucency.

Keywords: Radiography, Dental, Digital; Reproducibility of Results; Diagnostic Imaging.

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Introduction

The technique of digital radiography is similar to that of conventional (analogic) radiology; however, a computer is substituted for the chemical processing phase. This substitution is advantageous because it eliminates technical errors inherent in chemical processing. Other advantages of digital systems include fast processing and the ability to use the same sensor multiple times.[1,2,3,4,5,6] The image visualization programs used in digital radiography systems have various post-processing resources, enabling the user to alter brightness and contrast, rotate and amplify or reduce the image, invert the gray scale, apply pseudocolors to different gray tones, perform linear and angular measurements and quantify gray values in a region of interest (ROI).[5,6,7,8,9,10,11]

Damante *et al*.[10] developed a protocol for radiographic diagnosis and follow-up studies of simple bone cysts based on gray values. The authors evaluated ten patients and concluded that it is possible to apply a non-interventional follow-up protocol that avoids unnecessary surgery of these lesions. Ferreira Junior *et al*.[11] also performed a study using gray values for the diagnosis of simple bone cysts and

odontogenic keratocysts. However, gray values can vary, depending on the quality of the system used and on the exposure time.[6,7,8] As a result, these situations can compromise the diagnosis and follow-up studies of the lesions.

Various studies have evaluated the physical and clinical outcomes associated with digital systems under different conditions.[1,3,4,5,6,7,9,12,13,14,15,16,17] However, the current literature does not include studies of the reproducibility of gray values and noise associated with the Visualix eHD system when using gray values analysis to diagnose and track lesions.[8,10,11,12] Therefore, the objective of this study was to evaluate the reproducibility of the gray values and noise associated with the Visualix eHD system when varying the exposure times and the regions analyzed.

Methodology

For this study, the charge-coupled device (CCD) sensor (universal size) of the Visualix eHD system (Gendex Dental Systems, Lake Zurich, USA) was used, which had dimensions of 37.5 × 25.5 mm, a pixel size of 19.5 µm and a spatial resolution of 25.6 lp/mm. The CCD sensor was positioned in a phantom with a soft tissue simulator (acrylic), such that radiographic imaging could be performed in a standardized manner, without altering the position of the images. The dental X-ray machine (Kaycor X-707, Yoshida Dental MFG Co. Ltd., Tokyo, Japan) was operated with 70 kV, 7 mA, 2.2 mm filtration and a focus-film distance of 30 cm. A stepwedge with three steps, corresponding to 0.2, 0.4 and 0.6 mm of thickness, was coupled to the sensor. Ten consecutive radiographic images were acquired without altering the position of the sensor for each exposure time selected (0.05, 0.07, 0.09 and 0.13 s) (Figure 1).

Radiographic images were obtained, processed and stored in TIFF format (with no compression) and opened in the ImageJ program (National Institutes of Health, Washington, USA) on a computer with a 15-inch monitor (Satellite, Toshiba, Tokyo, Japan). For each image, five areas corresponding to ROIs were opened in the same square format (102 x 102 pixels), including three steps of the stepwedge (S1, S2 and S3), one for soft tissue (ST) and one for alveolar bone (AB) (Figure 2). All of the areas were saved so that their sizes and formats would be maintained for all measurements. The mean gray values of the ROIs were determined using the Analyse/Measure tool of the ImageJ program.[5,6,7,8,10,11]

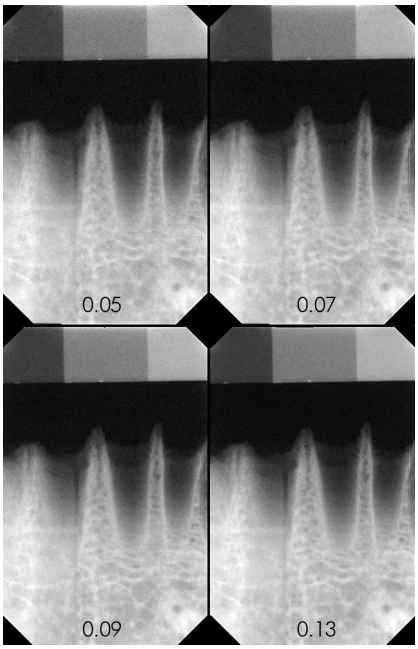

Figure 1. Images of the different groups.

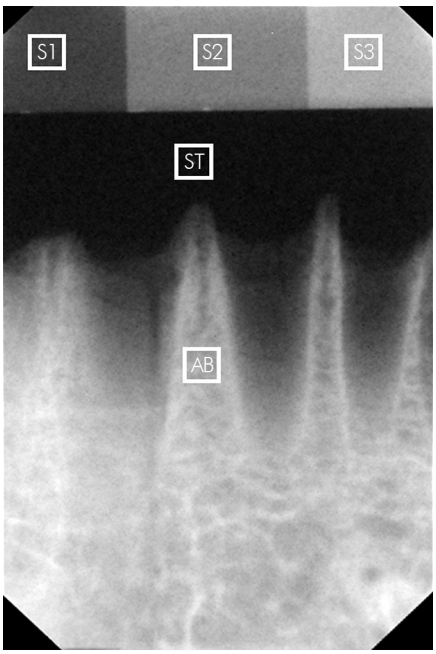

Figure 2. Definitions of the regions of interest (ROIs).

To analyze the reproducibility of the gray values, the following formula was used: (highest difference/mean) × 100. The highest difference corresponds to the mean gray value minus the lowest gray value or the highest gray value minus the mean gray value in the ROI on each image.[5] The mean, highest and lowest gray values were obtained after ten consecutive scannings of the sensor for each of the four exposure times and for each of the five regions. The noise was calculated in the ROI of the images. The formula applied to calculate the noise was: (standard deviation [SD]/gray value) × 100.[8] The means of the standard deviation and gray value for each ROI were obtained from ten consecutive radiographic images.

The reproducibility of the gray values and noise for the various exposure times and for each region analyzed were compared using analysis of variance (ANOVA). All statistical analyses were performed using Statistica for Windows 6.0 (Statistica for Windows, StatSoft Inc., Tulsa, USA). Statistically significant differences were defined as those with $p < 0.05$.

Results

Table 1 shows the results of comparisons of the gray values for various exposure times and ROIs. There were no significant differences between mean gray values evaluated for analyzed ROIs and exposure times ($p > 0.05$).

There were no significant differences in the reproducibility of the gray values for each ROI at the different exposure times ($p > 0.05$). However, there was a significant difference in the reproducibility between the soft tissue ROI and the other four ROIs ($p = 0.000$) at all four exposure times (Table 2).

Different letters in the vertical direction represent statistically significant differences (Tukey's test).

There were significant differences in the noise values between the different exposure times and ROIs ($p < 0.05$) (Table 3).

Different uppercase letters in the horizontal direction represent statistically significant differences (Tukey's test).

Different lowercase letters in the vertical direction represent statistically significant differences (Tukey's test).

Table 1. Comparison of the gray values in the various exposure times and ROIs (ANOVA).

Exposure time (s)	0.05				0.07				0.09				0.13				p
	Minimum	Maximum	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum	Mean	SD	
Alveolar bone	191.58	193.90	192.96	0.68	192.30	194.24	193.30	0.63	192.67	194.08	193.42	0.47	192.66	194.29	193.21	0.53	0.695
Soft tissue	21.72	24.26	22.63	0.84	20.82	23.43	21.88	0.85	19.58	22.89	21.26	1.05	18.07	20.31	18.69	0.68	0.658
S1	82.64	85.37	84.14	0.89	82.45	84.17	83.36	0.57	81.66	83.61	82.74	0.59	79.85	81.82	80.42	0.55	0.394
S2	148.06	150.25	149.10	0.67	147.39	149.75	148.83	0.76	147.64	149.31	148.74	0.56	146.55	148.42	147.19	0.46	0.508
S3	191.21	194.05	192.98	0.85	192.47	194.79	193.53	0.74	192.45	194.23	193.35	0.48	191.84	194.01	192.41	0.58	0.348

SD: Standard deviation.

Table 2. Comparison of the reproducibility of the gray values in the various exposure times and ROIs.

Exposure time (s)	0.05		0.07		0.09		0.13		p
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Alveolar bone	0.35^{a}	0.18	0.29^{a}	0.18	0.20^{a}	0.12	0.19^{a}	0.09	0.309
Soft tissue	3.23^{b}	1.81	3.17^{b}	2.22	4.09^{b}	2.76	2.90^{b}	2.20	0.710
S1	0.92^{a}	0.54	0.57^{a}	0.38	0.59^{a}	0.39	0.51^{a}	0.46	0.223
S2	0.39^{a}	0.23	0.44^{a}	0.26	0.32^{a}	0.19	0.20^{a}	0.24	0.185
S3	0.36^{a}	0.25	0.30^{a}	0.24	0.20^{a}	0.15	0.19^{a}	0.23	0.309
P	0.000		0.000		0.000		0.000		

SD: Standard deviation.
Different letters in the vertical direction represent statistically significant differences (Tukey's test).

Table 3. Comparison of the noise in the various exposure times and ROIs.

Exposure time (s)	0.05		0.07		0.09		0.13		p
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Alveolar bone	$4.89^{A,a}$	0.11	$4.95^{A,a}$	0.12	$4.98^{A,a}$	0.09	$5.17^{B,a}$	0.08	0.000
Soft tissue	$26.30^{A,B,b}$	1.12	$25.53^{A,B,b}$	1.41	$25.08^{A,b}$	1.02	$26.88^{B,b}$	1.00	0.010
S1	$6.25^{A,c}$	0.16	$5.84^{B,c}$	0.17	$5.61^{C,c}$	0.16	$5.18^{D,a}$	0.11	0.000
S2	$3.09^{A,d}$	0.09	$2.82^{B,d}$	0.07	$2.60^{C,d}$	0.09	$2.33^{D,c}$	0.11	0.000
S3	$2.13^{A,e}$	0.06	$1.91^{B,e}$	0.09	$1.75^{C,e}$	0.04	$1.50^{D,d}$	0.07	0.000
p	0.000		0.000		0.000		0.000		

SD: Standard deviation.
Different uppercase letters in the horizontal direction represent statistically significant differences (Tukey's test).
Different lowercase letters in the vertical direction represent statistically significant differences (Tukey's test).

Discussion

No studies to date have physically analyzed the reproducibility of the gray values and noise associated with the Visualix eHD system. The results of this study demonstrate the reproducibility of the gray values and noise for the system in five regions of radiographic imaging when the exposure time was varied.

Our study did not detect a statistically significant difference between the gray values with different exposure times, perhaps because there was relatively little variation in the exposure times selected (ranging from 0.05 to 0.13) or because the phantom with the soft tissue simulator attenuated the radiation.[5] According to Pietrobelli *et al*.[18] attenuation occurs when the photon signal crosses an element, chemical component or solution, spontaneously reducing the intensity through atomic interactions and leading to the absorption and dissipation of photons. Thus, when an X-ray beam penetrates an analyzed region, the presence of soft and hard tissues in this trajectory influences the gray values. In this study, the highest gray values were observed in the most radiopaque regions (AB and S3), and the lowest values were observed in the most radiolucent regions (ST and S1)[5,8,16,17] (Table 1).

No significant differences were found between the reproducibility of the gray values ($p \geq 0.185$) for various exposure times (0.05, 0.07, 0.09 and 0.13 s), because the gray values were not influenced by the exposure times. However, the reproducibility of the gray values did vary between the soft tissue ROI and the other four ROIs ($p = 0.000$). This result demonstrated that the variability of the gray shades after consecutive repetitions of the same ROI was greater in more radiolucent ROIs (Table 2). The higher mean variability of the gray shades for the Visualix eHD system in this study was 4.09%, which is lower than the results reported for the Digora system, *i.e*., 75% by Freitas *et al*.[5] and 27.95% by Teixeira *et al*.[17]

The lack of reproducibility of gray values of radiographic systems could be deleterious when limitations are unknown, because the system could potentially attribute differences in gray values as corresponding to a true change in the clinical condition of a patient. This situation could compromise the diagnosis and follow-up studies when a quantitative analysis of gray values is used,[5] with clinical implications. For example, when a carious lesion is relatively large, the area analyzed will be more radiolucent, and there will be greater variation in gray values. In contrast, when gray values analysis is used to evaluate the evolution of bone lesions,[10,11] the area analyzed will be more radiopaque, leading to lower variability of the gray values and more accurate analysis using the Visualix eHD system. This finding is supported by the studies of Damante *et al*.[10] and Ferreira Junior *et al*.[11] which proposed a protocol for the radiographic diagnosis and follow-up of simple bone cysts and odontogenic keratocysts based on gray values of the images.

A key factor for successful radiographic imaging is that the X-ray signal detected by the sensor must overcome the inherent noise of the digital radiographic system.[6] Noise is the undesirable fluctuation of pixel intensities, which can compromise the image studied,[12,17] thereby affecting the grey-scale intensity and, consequently, the gray values.[6,7,17] Noise levels can vary, depending on the quality of the system used[6,7,8] and the exposure time.[6] Moreover, noise levels can be evaluated using various physical parameters, such as the standard deviation.[6,7]

In this study, we identified differences in noise levels for various exposure times and ROIs. The noise decreased with increasing exposure times for the three areas of the stepwedge (Table 3). This finding differs from a study by Wenzel,[6] which found an increase in noise with an increase in exposure time from 0.20 to 0.60 s. The reason for this difference is based on the dose of radiation needed to saturate the sensor used in each of these studies.[6] In our study, the exposure times were smaller (ranging from 0.05 to 0.13 s), whereas the study by Wenzel's had longer exposure times (ranging from 0.20 to 0.60 s). On the other hand, our study found that the noise was statistically significantly greater when the area analyzed was more radiolucent (*i.e.*, soft tissue). These findings are in accordance with the results reported by Rubira-Bullen *et al*.[8] for digital radiographic images. Thus, as observed in the analysis of the reproducibility of the gray values in this study, as the noise of the system used increases, the interference for the quantitative analysis of the gray values also increases, especially in radiolucent lesions, such as dental caries.

This study did not assess the stability of the output power of the dental X-ray machine used. However, any instability of the machine was not sufficient to alter the reproducibility of the gray values or the noise.

Studies that evaluate the physical analysis of the radiographic systems are important to show the limitations and improve the diagnosis of lesions and follow-up studies.

Conclusions

Based on the methods used, the reproducibility of the gray values and noise of the Visualix eHD system can vary in specific areas with different radiolucency.

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