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Correlation analysis between radiation exposure and the image quality of cone-beam computed tomography in the dental clinical environment

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ABSTRACT

Purpose: This study was conducted to measure the radiation exposure and image quality of various cone-beam computed tomography (CBCT) machines under common clinical conditions and to analyze the correlation between them.

Materials and Methods: Seven CBCT machines used frequently in clinical practice were selected. Because each machine has various sizes of fields of view (FOVs), 1 large FOV and 1 small FOV were selected for each machine. Radiation exposure was measured using a dose-area product (DAP) meter. The quality of the CBCT images was analyzed using 8 image quality parameters obtained using a dental volume tomography phantom. For statistical analysis, regression analysis using a generalized linear model was used.

Results: Polymethyl-methacrylate (PMMA) noise and modulation transfer function (MTF) 10% showed statistically significant correlations with DAP values, presenting positive and negative correlations, respectively ($P < 0.05$). Image quality parameters other than PMMA noise and MTF 10% did not demonstrate statistically significant correlations with DAP values.

Conclusion: As radiation exposure and image quality are not proportionally related in clinically used equipment, it is necessary to evaluate and monitor radiation exposure and image quality separately. ***(Imaging Sci Dent 2022; 52: 283-8)***

KEY WORDS: Radiation Exposure, Cone-Beam Computed Tomography, Diagnostic X-Ray, Quality Control

Introduction

Since its first introduction in the early-1980s, cone-beam computed tomography (CBCT) has been used in various fields.[1,2] CBCT was first applied in the dental field in the mid-1990s, and the scope of its application has been gradually expanded.[3-5] According to a 2019 research report in South Korea, CBCT was used 778,766 times in 2019, compared to 399,327 times in 2016.[6] As the usage of CBCT in the dental field has increased dramatically, the importance of equipment management has also been recognized.[7]

Individual countries have developed and implemented regulations to manage radiation exposure, including dental CBCT. In the United States, the United States Radiation Protection Committee presented data on the use, collective effective dose, and effective dose per person per year for each type of medical radiation in the 2019 National Council on Radiation Protection & Measurements (NCRP) 184 report.[8] In South Korea, the Korea Disease Control and Prevention Agency presents data on the exposure of the Korean population to diagnostic medical radiation.[6]

As the radiation dose to the patient should be as low as reasonably achievable, while simultaneously providing adequate image quality to enable accurate diagnoses,[9-11] efforts to evaluate and improve image quality have also been made. There are international programs for improving

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diagnostic imaging quality, such as the CT Accreditation Program of the American College of Radiology (ACR) in the United States of America.[12] There are also quality control programs with legal implications, such as the Mammography Quality Standards Act of the ACR.[13] In South Korea, the quality of clinical images obtained through medical radiation is examined by the Korean Institute for Accreditation of Medical Imaging (KIAMI).[14] Annual documentation and a hands-on evaluation (every 3 years) are performed according to the regulations of the KIAMI. However, there is no program in dentistry for image quality management; therefore, it is almost impossible to identify and manage the level of image quality of dental radiographic images. With the goal of evaluating and controlling the image quality of dental radiographic images,[15,16] Choi et al. investigated the clinical image quality of panoramic radiographs and analyzed the parameters that influenced overall image quality in 2012.[17]

Regulations of dental CBCT should fully consider the actual clinical use environment and the condition of the equipment. In general, it would be reasonable to suppose that image quality would be improved by using a higher radiation exposure amount; however, in recent years, various equipment has been developed with improved irradiation and post-processing methods that enable a reduction of the dosage without degrading image quality.[18] Furthermore, since each CBCT machine has preset sizes of fields of view (FOVs), and the exposure parameters can be used only in a preset form, the radiation exposure can vary regardless of image quality depending on the equipment's preset options. Accurate examinations with appropriate management of radiation exposure and image quality are possible only with an accurate understanding of their correlation in the actual clinical environment, where adjusting independent variables is often impossible. However, to the best of the authors' knowledge, no study has yet investigated this issue.

This study was conducted to measure radiation exposure using a dose-area product (DAP) meter and image quality values using a dental volume tomography (DVT) phantom under the conditions commonly used in the clinical environment with various CBCT machines. The correlations between DAP values and image quality values in the clinical environment were statistically analyzed. Since the purpose of this study was not to obtain basic scientific data on the relationship between these variables, but to confirm whether the general concept regarding the association of the radiation dose and image quality is actually reflected in the real clinical environment, clinically used preset conditions and FOVs were used rather than adjusting these parameters arbitrarily.

Materials and Methods

Selection of CBCT machines and FOVs

The following 7 CBCT machines commonly used in clinical practice[19] were selected: CS8100 (Carestream, Rochester, NY, USA), Eco-X (HDX, Seoul, Korea), Green X (Vatech, Seoul, Korea), Orthopro (Sirona, York, PA, USA), Rainbow (Dentium, Seoul, Korea), T1 (Osstem, Seoul, Korea), and Viso G7 (Planmeca, Helsinki, Finland). The Vatech Green X device had 2 types of exposure methods: normal mode and green (low-dose) mode. These were analyzed separately as different CBCT types; therefore, 8 CBCT types were examined.

Because each machine had various sizes of FOVs and it was impossible to adjust them arbitrarily, representative FOVs were selected by asking clinicians about the FOVs commonly used to evaluate the overall condition in adult male patients and to plan implant insertion in the maxillary first molar area in actual clinical settings. The 2 most frequently used FOVs were selected by classifying the long axis into ranges, with the long axis from 11 to 16 cm (large FOV) or from 8 to 9 cm (small FOV).

The total numbers of selected equipment and FOVs are listed in Table 1. Experiments were conducted under 12 conditions, as only 1 FOV size corresponded to the experimental range for 4 CBCT machines (CS8100, Eco-X, Rainbow, and Viso G7). The exposure parameters were set according to the manufacturer's recommendations for adult males. For each condition, the FOV size, voxel size, exposure time, tube voltage (kVp), and tube current (mA) were recorded.

Measurement of the radiation exposure

The radiation exposure for each CBCT machine was measured using a DAP meter, KermaX plus (IBA Dosimetry, Schwarzenbruck, Germany) (Fig. 1). The DAP meter was calibrated at the manufacturer's headquarters in Germany within 3 months of the experiment, and the calibration value presented in the report was used as a calibration factor. The DAP values were measured 3 times under the same conditions, and the average was recorded to minimize the error.

Image quality evaluation

The quality of the CBCT images was evaluated using a DVT phantom (Quart GmbH, Zorneding, Germany). The DVT phantom was mounted using a fabricated mounting table with a flat top and positioned using a 3-axis horizontal system (Fig. 2). The acquired images were analyzed using DVT TEC software (Quart GmbH, Zorneding, Germany). Eight image quality values were obtained and analyzed:

Table 1. Obtained values for 12 conditions on 8 cone-beam computed tomography (CBCT) types (blinded with A-H) arranged in ascending order of dose area product (DAP) values

CBCT types	A	B	A	C	B	D	E	F	C	D	G	H
FOV (cm × cm)	8 × 8	8 × 8	11 × 10	8 × 8	16 × 9	9 × 8	8 × 8	16 × 10	16 × 9	15 × 9	16 × 9	16 × 9
Voxel size (mm)	0.16	0.12	0.16	0.12	0.2	0.2	0.075	0.2	0.2	0.2	0.2	0.1
DAP (cGy cm^2)	10.63	57.4	73.86	94	115	130.82	135.58	146.91	159.5	215	222.51	498
PMMA average	939.5	779.5	614.6	839.7	1169.7	660.2	909.3	1139.3	967.6	711.7	1450.5	989.5
PMMA noise	28.4	68.5	12.1	45.2	36.6	55.6	85.2	56.3	28.1	46.626	72.1	92.8
Homogeneity	15	6	12	11	18	16	31	17	15	26	18	13
Contrast	456.4	997.4	480.5	1029.8	1006.2	882.1	715	830.7	958.4	885.7	951.5	681.8
CNR	8.5	15.8	8.9	17.2	16	11.3	10	13.3	20.9	11.1	13	7.3
MTF 10%	2.3	2.6	2.1	2.7	2.2	1.8	2.1	1.6	2.3	1.8	2	1.6
MTF 50%	0.9	1.2	0.9	1	1.1	1	1	0.7	1.3	1	1.2	0.8
NF	3.1	4.1	2.3	4.1	2.5	2.5	3.3	1.6	2.5	2.5	2.5	2.5

FOV: field of view, PMMA: polymethyl-methacrylate, CNR: contrast-to-noise ratio, MTF: modulation transfer function, NF: Nyquist frequency

Fig. 1. A flat plane ionization chamber of a dose-area product meter is attached to the source side of the cone-beam computed tomography device.

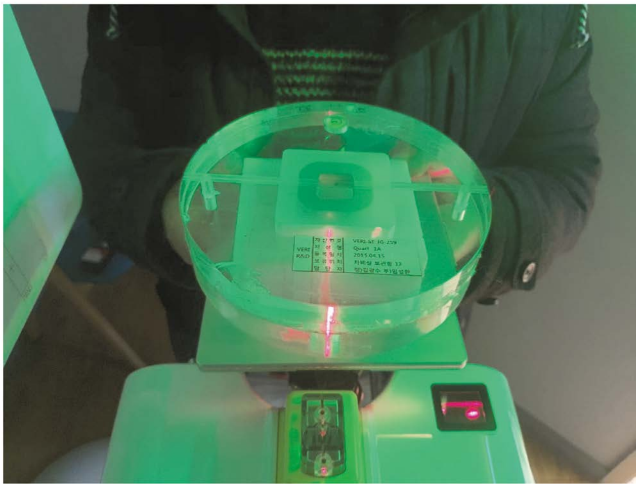

Fig. 2. A dental volume tomography phantom is positioned using a fabricated mounting table with a flat top. The center of the phantom is positioned at the center of the field of view of the cone-beam computed tomography device.

polymethyl-methacrylate (PMMA) average, PMMA noise, homogeneity, contrast, contrast-to-noise ratio, modulation transfer function (MTF) 10%, MTF 50%, and the Nyquist frequency.

Statistical analysis

Regression analysis using a generalized linear model (GLM) was performed to analyze the associations between DAP values and the 8 image quality values. A GLM is a flexible generalization of ordinary linear regression that enables the response variable to have an error distribution other than the normal distribution. The GLM generalizes linear regression by allowing the linear model to be related to the response variable via a link function and by allowing the variance of each measurement to be a function of its predicted value. The GLM method was used because there were only 12 samples of explanatory variables, DAP values, and dependent variables (i.e., the 8 image quality values).

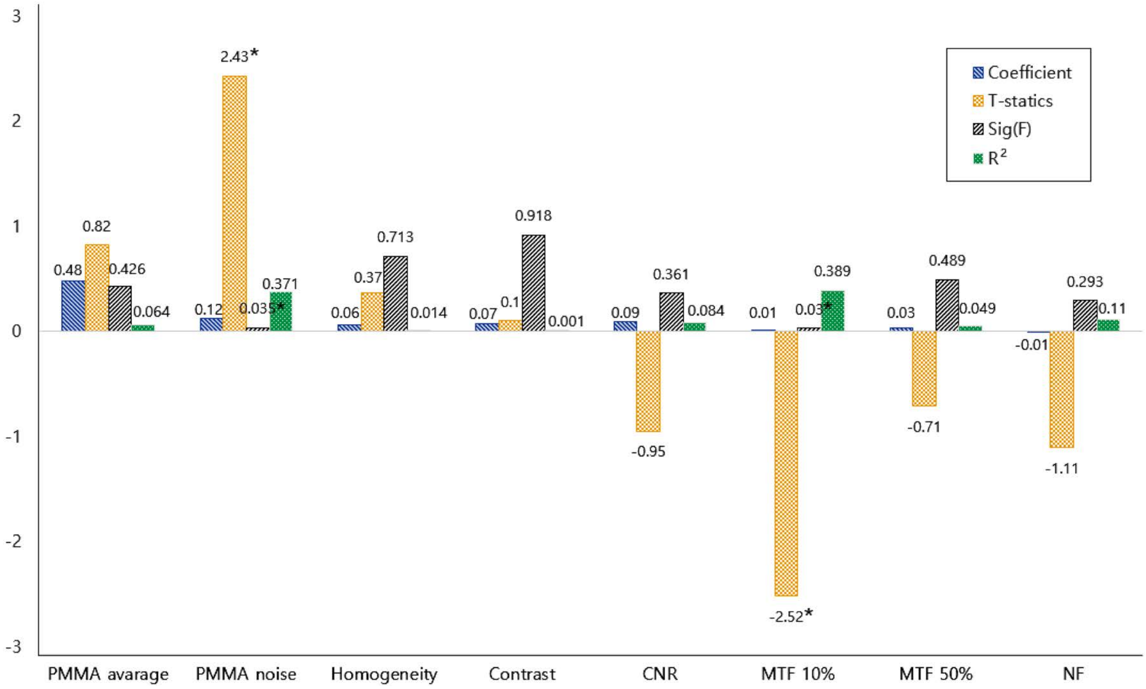

Fig. 3. Bar graph shows the results of regression analysis using a generalized linear model. *: $P<0.05$, PMMA: polymethyl-methacrylate; CNR: contrast-to-noise ratio; MTF: modulation transfer function; NF: Nyquist frequency.

Results

The obtained values are listed in Table 1. The results of the experiments for 12 conditions on 8 CBCT types were arranged in ascending order of DAP values. The names of company and model were blinded with alphabets (A-H), because the experiments were conducted under the clinical conditions rather than the optimized conditions and results may not reflect the actual characteristics of each equipment. The average DAP value was 154.93 ± 118.72 cGy cm^2. The difference between the lowest DAP value (10.63 cGy cm^2) and the highest DAP value (498 cGy cm^2) was 46.85 times.

Within a single device, as the size of the FOV increased, the DAP value tended to increase. When comparing several devices together, similarly, larger FOV sizes generally tended to result in higher DAP values.

However, there were some exceptions; for example, in the case of CBCT B with the FOV size of 16 cm × 9 cm, the DAP value was lower than that of CBCT D with the FOV size of 8 cm × 8 cm or CBCT E with the FOV size of 9 cm × 8 cm.

Figure 3 shows the results of the GLM statistical analysis. Two of the image quality values, PMMA noise and MTF 10%, had significant correlations with DAP values. The regression model of PMMA noise showed a significant positive correlation with DAP values ($P<0.05$), and the explanatory power was 37.1% ($R^2=0.371$). MTF 10% presented a significant negative correlation with DAP values ($P<0.05$), and the explanatory power was 38.9% ($R^2=0.389$). None of the other image quality parameters showed statistically significant correlations with DAP values.

Discussion

In general, it is assumed that higher levels of radiation exposure are associated with better image quality.[20] However, the results of this study showed that radiation exposure and image quality did not show a consistent correlation and that radiation exposure was not associated with significant differences in image quality parameters other than PMMA noise and MTF 10%. Furthermore, PMMA noise and MTF 10% showed significant positive and negative correlations, respectively, with DAP values. This finding is opposite to the expectation that noise would decrease and MTF would improve as radiation levels increased. There are several possible reasons for this result. First, improvements in irradiation and post-processing methods are a possible explanation. Second, equipment aging and damage occur in a clinical use environment, which may lead to increased exposure and reduced image quality. Third, as each CBCT device has preset exposure parameters and FOVs, the radiation exposure can vary regardless of image quality depending on the preset options. For example, when trying to obtain general information on the jawbone, the radiation exposure will depend on the preset size of large FOV of the equipment, even if it has the same image quality.[21]

Several additional considerations should be kept in mind when interpreting the results of this study. First, because the exposure parameters and the size of FOVs provided by each machine were different and often impossible to adjust arbitrarily, it was challenging to fine-tune changes in the independent variable. Thus, given the difficulty of accurately controlling the experiment, an accurate comparative analysis would require the manufacturers to modify the equipment. However, in clinical environments, images are only acquired using the preset exposure modes provided by the manufacturer, rather than by controlling various variables; therefore, this aspect of the study design can be considered as a good reflection of the actual clinical environment. Nonetheless, a separate study would be needed to investigate how much each parameter can be set as an independent variable and to what extent the obtained dependent variable can be recommended as an acceptable range. Second, the machines used in this experiment had been used for various lengths of time and were not tested under the most optimized conditions; therefore, the results may not be reflective of the true characteristics of each machine. However, they were tested under actual clinical conditions and the machines used in the experiment were all manufactured after 2017. As the devices all passed the standards of the Korea Food and Drug Administration, it would be difficult to attribute the findings of this study only to equipment aging. Third, as several machines were tested, the DVT phantom image could not be obtained multiple times from the same machine due to time limitations. Addressing this limitation would require additional repetitive experimental images and research using sufficient quantities of machines. The results of this study will facilitate further research on how to improve image quality while reducing radiation exposure and how to accurately regulate the radiation dose and image quality.

In conclusion, the DAP values and image quality values showed no consistent correlations, and radiation exposure was not associated with significant differences in values other than PMMA noise and MTF 10%. As radiation exposure and image quality are not proportionally related in the machines that are used clinically, it is necessary to accurately evaluate and monitor radiation exposure and image quality separately.

Conflicts of Interest: None

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