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Evaluating the index of panoramic X-ray image quality using K-means clustering method

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Abstract

Background A panoramic X-ray image is generally considered optimal when the occlusal plane is slightly arched, presenting with a gentle curve. However, the ideal angle of the occlusal plane has not been determined. This study provides a simple evaluation index for panoramic X-ray image quality, built using various image and cluster analyzes, which can be used as a training tool for radiological technologists and as a reference for image quality improvement.

Results A reference panoramic X-ray image was acquired using a phantom with the Frankfurt plane positioned horizontally, centered in the middle, and frontal plane centered on the canine teeth. Other images with positioning errors were acquired with anteroposterior shifts, vertical rotations of the Frankfurt plane, and horizontal left/right rotations. The reference and positioning-error images were evaluated with the cross-correlation coefficients for the occlusal plane profile, left/right angle difference, peak signal-to-noise ratio (PSNR), and deformation vector fields (DVF). The results of the image analyzes were scored for positioning-error images using K-means clustering analysis. Next, we analyzed the correlations between the total score, cross-correlation analysis of the occlusal plane curves, left/right angle difference, PSNR, and DVF. In the scoring, the positioning-error images with the highest quality were the ones with posterior shifts of 1 mm. In the analysis of the correlations between each pair of results, the strongest correlations ($r = 0.7–0.9$) were between all combinations of PSNR, DVF, and total score.

Conclusions The scoring of positioning-error images using K-means clustering analysis is a valid evaluation indicator of correct patient positioning for technologists in training.

Keywords Quality improvement, Signal-to-noise ratio, Panoramic X-ray images, Cluster analysis, Occlusal plane

Background

In dentistry, panoramic X-ray imaging provides a comprehensive view of all teeth, helping detect lesions in the oral region effectively [1]; this imaging modality scans the oral and maxillofacial areas using the tomographic technique with a narrow-slit X-ray beam [2].

This technique allows to image specific tomographic planes by selecting an appropriate trajectory of the rotating X-ray beam, while irrelevant adjacent and overlapping cross-sections are blurred in the resulting image [1]. With this imaging method, the blurred areas and the regions out of focus differ depending on the X-ray incidence angle and on the jaw shape. Thus, an accurate positioning technique should be adopted by radiological technologists to obtain high-quality images [3].

The imaging method for panoramic radiograms uses different tomographic widths depending on the position of the image focus in relation to the dentition in several rotational activations. Moreover, the degree of image blurring of panoramic X-ray images depends on the different distance between the image receptor and

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the anterior segment of the dental arch possibly due to positioning errors [4]. The methods previously proposed to evaluate positioning errors include the peak signal-to-noise ratio (PSNR), which examines the image signal quality and legibility, and frequency analysis, evaluating the images in the frequency domain [5, 6].

A panoramic X-ray image is generally considered optimal when the occlusal plane is slightly arched, presenting with a gentle curve or "smile line" [7, 8]. However, the ideal angle of the smile line for the occlusal plane relate to diagnostic ability and image quality has not been determined [9, 10]. Moreover, few reports have objectively evaluated the relationship between the angle of the occlusal plane and the visibility of the teeth crowns, roots, alveolar bone, and lesions [8]. Inadequate images may be caused by differences in the rotational trajectories of the X-ray machines or positioning errors [9]. However, evaluating the varying image quality due to small rotational deviations or positioning errors is challenging [9, 10]. A previous study examined the image quality for the classification of dental problems using deep learning [11]; nonetheless, the image quality may be improved by repositioning the panoramic X-ray machine and understanding the relationship between the specific smile-line angle and image quality. This knowledge may also improve the image reproducibility among different technicians in clinical practice.

Positioning errors may occur in several dimensions, such as the center of the tomographic field not corresponding to the anatomical center, vertical misalignments, and rotational differences [8, 11]. An objective evaluation of the influence of each type of error may help improve the quality of panoramic X-ray images. Deformable image registration (DIR) is a process to evaluate misalignment by comparing the images to a reference, helping detect tooth enlargements or misalignments due to imaging differences [12, 13]. The advantage of DIR has numerical value of the deformation vector field (DVF) which results of warp between the reference and positioning error images [12, 13].

The most appropriate angle of the occlusal line in a panoramic X-ray image has not been defined, and thoroughly evaluating and comparing the quality of these images is difficult. In addition, these radiographs are often acquired in series for a patient and compared over time; therefore, image reproducibility is essential [14, 15]. Therefore, we evaluated the effect of slight positioning errors on the image quality using a phantom and cross-correlation coefficients of the occlusal plane profile, left/right angle difference, PSNR, and vector displacement of the images [5, 12]. To the best of our knowledge, no previous reports evaluated the image quality using DIR and PSNR or used image evaluation to improve the quality of these images. This study provides a simple index to evaluate panoramic images at the time of acquisition and can be used as a training tool for radiological technologists to improve image quality [11, 16].

Methods

Reference image

The panoramic X-ray images were acquired using a panoramic machine (Morita, Kyoto, Japan) and a human-bones phantom, with the Frankfurt plane positioned horizontally, and the frontal plane centered on the canine teeth. We followed previously established guidelines for an ideal image, with the occlusal plane displayed as a slight curve or smile line and the mandible presenting as U-shaped [8]. The workflow of this study is illustrated in Fig. 1.

Images with positioning errors

Three groups of images with positioning errors were acquired, as shown in Fig. 1. First, the center of the frontal plane was shifted from the canine teeth anteriorly or posteriorly by 1, 2, 3, 4, and 5 mm. Then, images with high and low chin misplacement were acquired by rotating the Frankfurt plane vertically by 2°, 4°, 6°, 8°, and 10°. Finally, images with right/left head rotation were acquired by rotating the phantom on the horizontal plane by 2°, 4°, 6°, 8°, and 10° in either direction. These images were evaluated for occlusal plane profile, angle difference between left and right sides, PSNR, and deformation vector fields (DVF) using ImageJ/Fiji (version: 1.53f51, National Institutes of Health, Bethesda, MD, USA).

Cross-correlation analysis of the occlusal planes between the reference and positioning-error images

The occlusal plane profiles of the positioning-error images were plotted three times by a radiological technologist using ImageJ/Fiji, and the measures were averaged (Fig. 2). The cross-correlation coefficients between the curve of the reference image and those of the positioning-error images were calculated (Fig. 2). The cross-correlation coefficients were calculated using the following equation:

$$\text{Cross}-\text{correlation coefficient}\,(X,Y)=\frac{\sum(x-\bar{x})\sum\left(y-\bar{y}\right)}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}}. \quad (1)$$

The left/right angles of each image were calculated from the curve of the occlusal plane, as shown in Fig. 1. Moreover, the differences in the angles between the reference image and positioning-error images were determined.

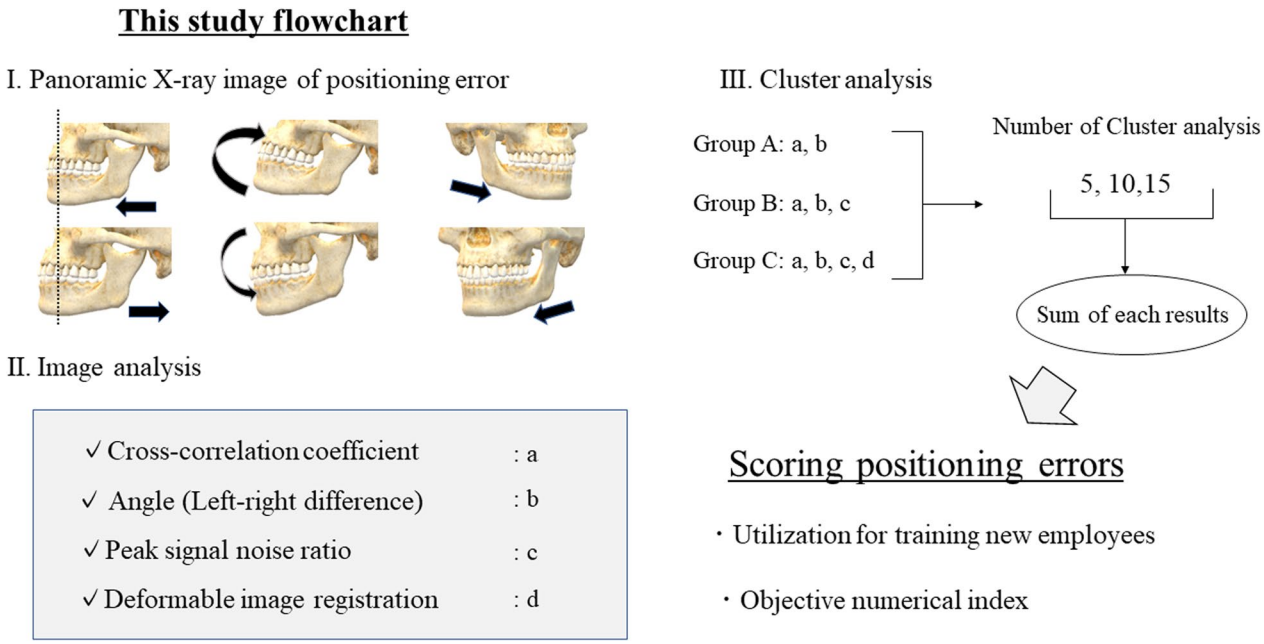

Fig. 1 The study workflow

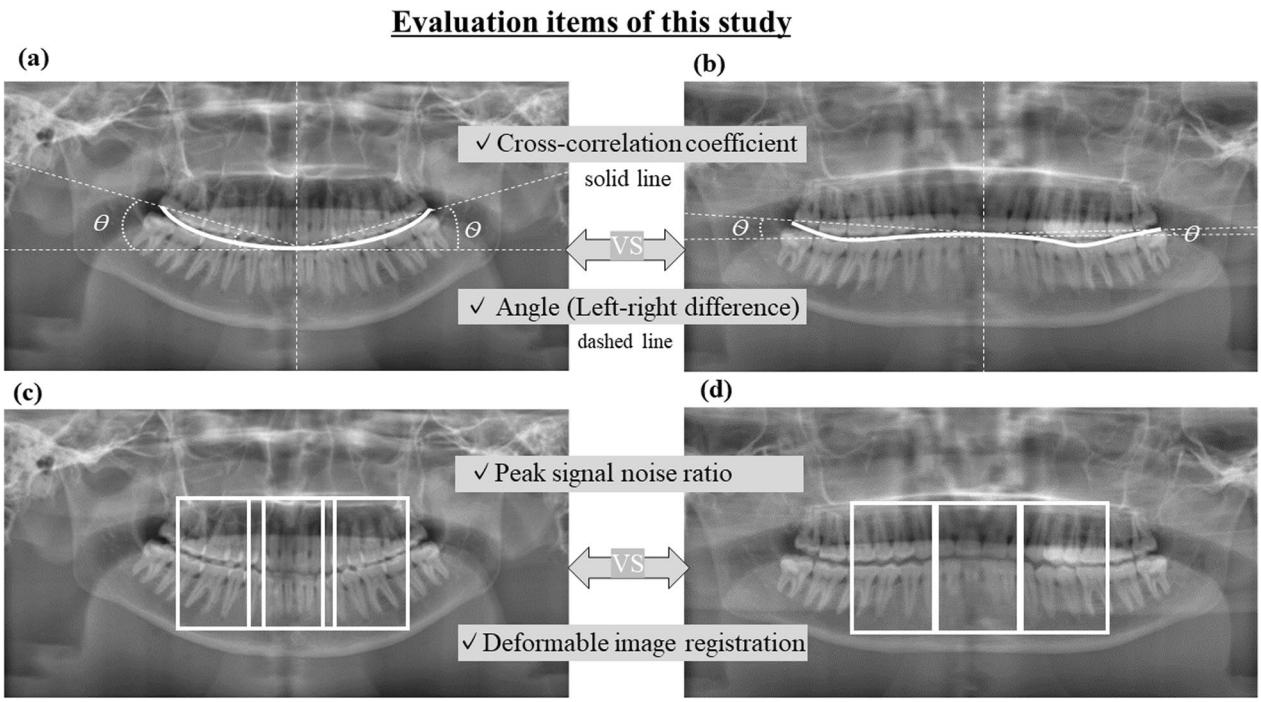

Fig. 2 Parameters used for evaluation. **a** Profile and angles of the occlusal plane in the reference panoramic X-ray image. **b** Profile and angle of the occlusal plane in an image with superior rotation. **c** Setting of the region of interest in the reference image. **d** Setting of the region of interest in an image with superior rotation

PSNR analysis of the positioning-error images and calculation of the DVF

The reference and positioning-error images were divided into three regions of interest (ROIs) for these analyzes (region size: 10 cm × 15 cm, position: right premolars and molars 4, 5, 6; incisors 2, 2; left premolars and molars 4, 5, 6), as shown in Fig. 2. The PSNR was calculated in each ROI using the following equation:

$$\mathrm{PSNR} = 10 \times \log_{10} \frac{\mathrm{MAX}^2}{\mathrm{MSE}}, \tag{2}$$

where MAX is the maximum possible pixel value of the image, and MSE is the mean squared error between the original and the corrupted signals.

Additionally, the positioning-error images were registered to the reference image in the three regions performing DIR with the bUnwarpJ algorithm of ImageJ/Fiji [17, 18]. The DVF was calculated to match any point of the deformed image with the corresponding point on the reference image using B-spline deformation [13, 17]. The displacement error obtained after deforming the positioning-error image with the vector field was used to create a vector map. The DVF was calculated using the following equation:

$$\mathrm{DVF} = \frac{1}{\#\Omega} \sum_{x \in \Omega} [Id\,(x) - Ii\,d(x)]^2, \tag{3}$$

where *Id(x)* is the point coordinate on the reference image, and *Iid(x)* is the corresponding target point coordinate on the positioning-error image.

The results of the cross-correlation analysis of the occlusal plane curves, left/right angle difference, PSNR, and DVF for the three ROIs were averaged to obtain the result of each evaluation. The PSNR was used evaluation of the blur image due to positioning error and shifts from the fault zone [5, 10]. The DVF was used evaluation of the displacement due to positioning error for the rotational trajectories and the shift of midsagittal plane [10, 13].

Scoring of positioning-error images using the K-means clustering analysis

The results of the image analysis were divided into three groups (group A: cross-correlation analysis of the occlusal plane curves and left/right angle difference; group B: PSNR, group C: group B and DVF). These groups were used to define clusters of results using a k-means clustering analysis. The k-means clustering analysis was performed in three different ways (number of clusters: 5, 10, and 15). The results of these three analyzes were scored based on the category of the highest cross-correlation coefficient, and the scores of the three analyzes were summed for each of the three groups. Furthermore, we summed the total scores of the three groups for each image analysis and evaluated them on a three-grade scale (○: ≥ 80%, △: ≥ 60%, and × : < 60%), based on the percentage of the maximum quality. Next, we analyzed the correlations between the total score of the three groups (cross-correlation analysis of the occlusal plane curves, left/right angle difference, PSNR, and DVF). The Pearson's linear correlation coefficients (r) were determined using JMP Pro 15 statistical software (SAS, Cary, NC, USA).

Results

Overall, the image quality decreased in relation to the amount of translation and rotation of the positioning error; the cross-correlation coefficients and PSNR decreased, while the left/right angle differences and DVF increased. The complete results are reported in Table 1.

The cross-correlation coefficients of the occlusal plane profile showed the highest value with a 1-mm posterior shift ($r = 0.999$), and the lowest value with a superior rotation (high chin) of 10° ($r = -0.267$). Figure 3 shows the occlusal plane profiles with inferior and superior rotations and the relative changes compared to the reference image. In the analysis of each parameter, the lowest score for the left/right angle difference (10.61°) was obtained with a 10° superior rotation; for the PSNR (15.8 dB) with a 10° right rotation, and for the DVF (596.5) with a 10° left rotation.

In the cluster analysis using cross-correlation coefficients, left/right angle difference, PSNR, and DVF, the highest scores were obtained in the image with 1-mm posterior shift. The 2° right-rotation image had the second overall highest scores; however, the DVF showed higher deformations (89.4 vs. 22.5 of the aforementioned image). The results of the cluster analysis were quantified and categorized on a three-grade scale; the images with posterior shifts of 1–4 mm had the highest quality (≥ 80%).

In the analysis of the correlations between each pair of results, the strongest correlations ($r = 0.7$–0.9) were between all combinations of PSNR, DVF, and group results of cluster analysis, and between the total score of group A for cluster analysis and left/right angle differences (Table 2, Fig. 4). In contrast, the cross-correlation coefficients of the occlusal plane profile had weak correlations with the PSNR ($r = 0.362$) and DVF ($r = -0.398$). The left/right angle differences had a moderate or high correlation with all image analyzes and scores.

As shown in Fig. 4a, the weak correlation between the cross-correlation coefficients of the occlusal plane profile and the total score of group C was an effect of the outlier for the 10° superior rotation.

Table 1 Image quality parameters of panoramic X-ray images with positioning errors

	Positioning error	Cross-correlation coefficient	Mean angle difference between left and right (°)	Mean PSNR	Mean DVF	Cluster analysis: Total score			Overall quality class[d]
						Group A[a]	Group B[b]	Group C[c]	
Anterior shift	1 mm	0.998	0.98	23.3	31.4	25	26	30	○
	2 mm	0.996	1.66	21.7	48.7	25	21	25	△
	3 mm	0.994	2.26	21.0	70.9	25	19	21	△
	4 mm	0.993	2.25	21.0	191.8	24	19	21	△
	5 mm	0.985	2.80	20.9	271.5	20	19	20	△
Posterior shift	1 mm	0.999	0.20	27.1	22.5	30	30	30	○
	2 mm	0.997	0.60	25.0	26.8	30	30	21	○
	3 mm	0.998	1.16	22.4	40. 9	25	27	25	○
	4 mm	0.996	1.22	21.2	58.7	25	25	25	○
	5 mm	0.995	1.54	20.6	176.4	24	25	21	△
Superior rotation	2°	0.995	2.63	22.4	84.1	24	24	20	△
	4°	0.986	3.55	18.9	121.4	20	16	23	△
	6°	0.828	5.56	18.0	243.8	9	6	8	×
	8°	0.691	6.25	17.7	364.5	6	6	5	×
	10°	-0.267	10.61	16.0	426.3	3	3	4	×
Inferior rotation	2°	0.985	0.02	18.5	186.1	21	19	21	△
	4°	0.984	2.49	18.4	220.2	11	18	23	×
	6°	0.983	4.61	18.1	260.5	9	17	21	×
	8°	0.983	6.03	17.3	322.9	13	17	21	×
	10°	0.977	7.73	16.8	353.8	13	16	15	×
Right rotation	2°	0.996	0.52	24.9	89.4	29	27	30	○
	4°	0.978	1.42	20.0	97.2	23	18	21	△
	6°	0.959	2.43	19.8	191.4	16	11	16	×
	8°	0.951	2.77	18.1	234.0	15	11	16	×
	10°	0.948	4.33	15.8	391.9	10	9	12	×
Left rotation	2°	0.996	0.32	22.1	52.0	24	22	30	△
	4°	0.976	1.28	21.6	122.0	24	22	22	△
	6°	0.971	1.48	18.8	215.4	15	13	16	×
	8°	0.963	2.04	17.5	353.4	16	13	14	×
	10°	0.960	2.17	16.4	596.5	12	13	14	×

[a] Cross-correlation analysis of the occlusal plane curves and left/right angle difference; [b]PSNR; [c]group B and DVF; [d]○: ≥ 80%; △: ≥ 60%; ×: < 60%. PSNR: peak signal-to-noise ratio; DVF: deformation vector fields

Discussion

In this study, we proposed a method for the objective evaluation of image quality in relation to positioning errors in panoramic X-ray imaging, using K-means clustering analysis and various types of image analysis.

Overall, the cross-correlation coefficients of the occlusal plane profile, left/right angle differences, PSNR, and DVF all indicated a lower image quality correlated with the amount of translation and rotation in the positioning-error images. In particular, the vertical rotations were the positioning errors with the greatest effect on the left/right angle difference due to the Frankfurt line deviation from the horizontal plane. In contrast, the DVF was affected mostly by the horizontal rotations, resulting in deformations and blurring due to the deviation from the tomography rotation axis [19]. The horizontal rotations affected each image analysis result possibly due to the uneven bone structure of the phantom.

The total score of the K-means cluster analysis indicates the overall deterioration of the image quality as a numerical value [20, 21]; this three-grade scale and the total score could also be used for the evaluation during the training of new radiological technicians. The three-grade scale and the total score should be adjusted for each facility due to differences in phantom shapes and rotational trajectories; nonetheless, accuracy is required to avoid positioning errors. In addition, this scoring can

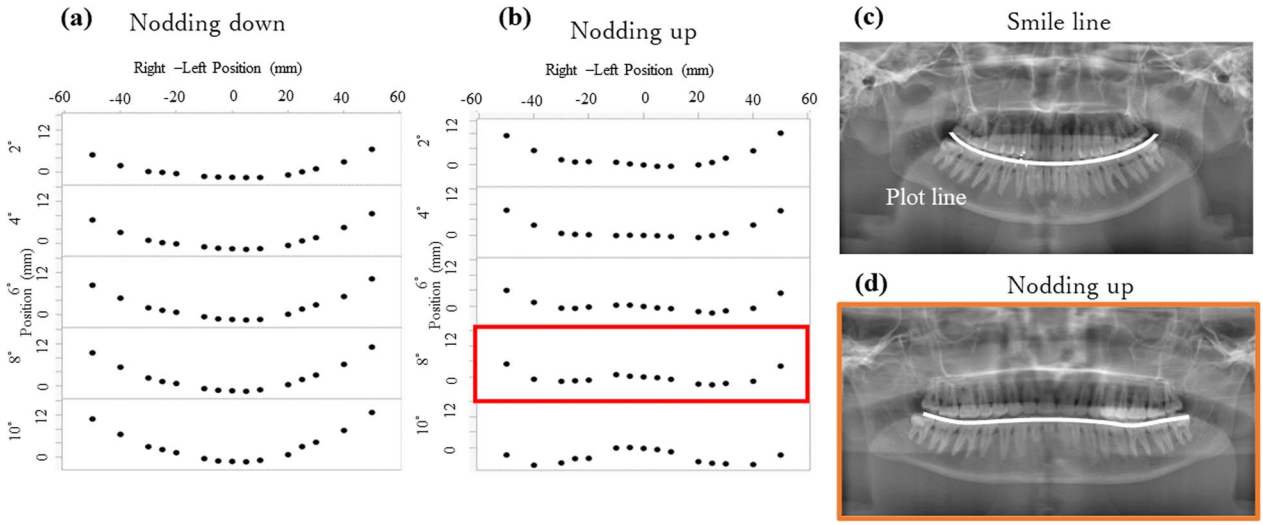

Fig. 3 Changes in the profile of the occlusal plane and examples of the profile in panoramic X-ray images. **a** Inferior rotation. **b** Superior rotation. **c** The smile line in the reference image. **d** The profile in a superior-rotation image

Table 2 Correlation coefficients for the relationship between evaluation indices

	Cross-correlation coefficient	Average angle difference between right and left (°)	Average PSNR	DVF	Cluster analysis		
					Group A[a]	Group B[b]	Group C[c]
Cross-correlation coefficient	–	−0.649	0.362	−0.398	0.535	0.545	0.596
Average angle difference between left and right (°)	−0.649	–	-0.648	0.603	−0.772	−0.617	−0.659
Average PSNR	0.362	−0.648	–	−0.835	0.886	0.858	0.756
DVF	−0.398	0.603	-0.835	–	−0.827	−0.758	−0.753
Cluster analysis: group A[a]	0.535	−0.772	0.886	−0.827	–	0.895	0.813
Cluster analysis: group B[b]	0.545	−0.617	0.858	−0.753	0.895	–	0.877
Cluster analysis: group C[c]	0.596	−0.659	0.756	−0.758	0.813	0.877	–

[a] Cross-correlation analysis of the occlusal plane curves and left/right angle difference; [b]PSNR; [c]group B and DVF. PSNR: peak signal-to-noise ratio; DVF: deformation vector fields

be used for the evaluation of optimal rotation trajectories among different panoramic X-ray machines.

In this study, the posterior shifts were the positioning errors maintaining the highest total score. Therefore, when the correct positioning is challenging, such as in patients without canines or after jaw deformity surgery, centering the frontal plane on the third tooth with a posterior rather than anterior shift may provide images with negligible quality deterioration.

The cross-correlation coefficient of the occlusal plane profile had a weak correlation with the PSNR and DVF. The left/right angle difference was moderately correlated with the PSNR, DVF, and cluster analysis results. The left/right angle difference caused by positioning errors may be evaluated with a simple index; however, a minor angle deviation of the occlusal plane profile is not an issue. The PSNR allows to quantify the image blur, and the DVF evaluates the direction of the required positioning-error correction using a vector map [5, 10]. The correlation coefficient between the total score and DVF was high, and the DIR vector map may visually show the required correction of the positioning error.

This study has some limitations. First, the inconsistencies of the image analysis results using only one kind of phantom and panoramic X-ray machine were due to the structural deviations of the phantom and restrictions on the rotational trajectory of the apparatus. The number of samples is small to achieve an absolute evaluation indicator for the positioning error. However, this method can be used by instructors to acquire reference images for each facility for the training of new technologists. Moreover, the images were acquired using a phantom instead of using clinical images; therefore, the effect of individual tooth and bone shape differences could not

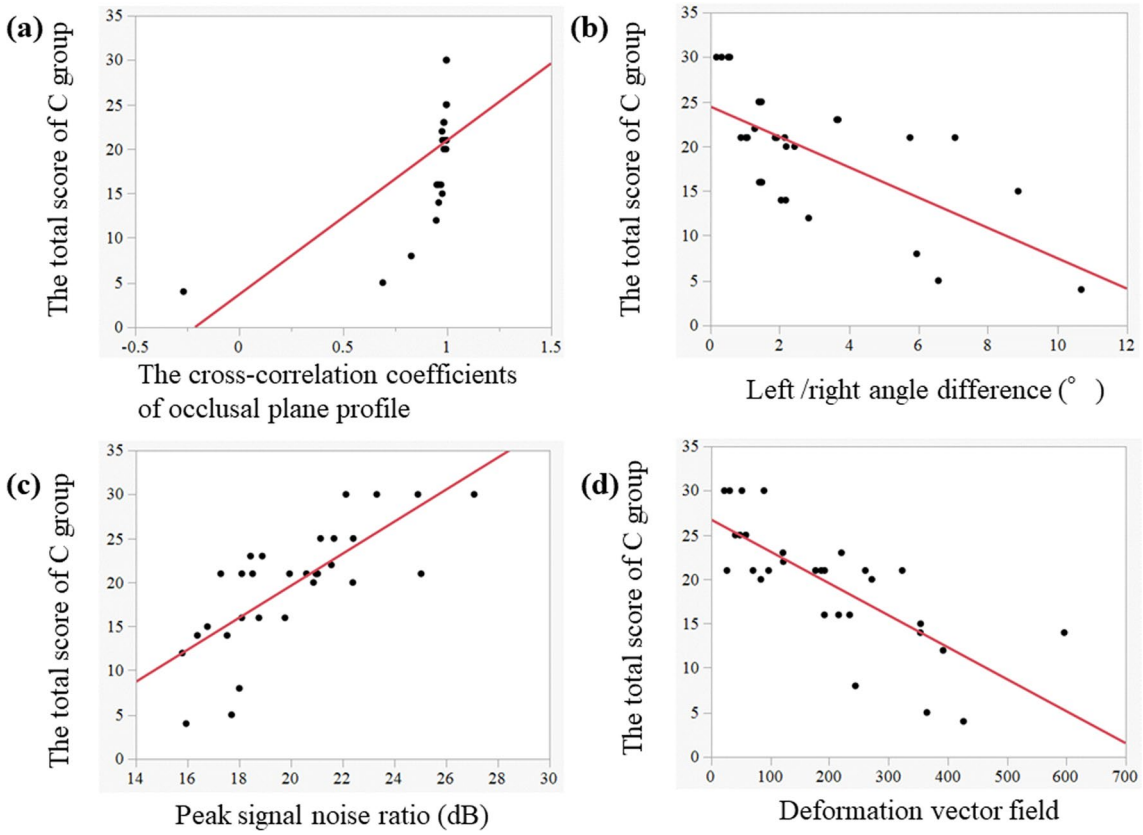

Fig. 4 Correlations between the results of different data analyzes and the total score of C group. **a** The Cross-correlation coefficients of occlusal plane profile and the total score of C group. **b** Correlation between left/right angle difference and the total score of C group. **c** Peak signal noise ratio and the total score of C group. **d** Deformation vector field and the total score of C group

be considered. In addition, the influence of complex positioning errors was not evaluated. For future studies, the cross-correlation coefficients of occlusal plane profiles and left/right angle differences must be evaluated using clinical images of patients to obtain more reliable data.

Panoramic X-ray images have been studied using artificial intelligence [22], and several methods have been used to evaluate the image quality. Our study provides a simple reference for radiological technologists to understand the effect of positioning errors and different occlusal plane angles on the image quality.

Conclusions

The differences in occlusal plane angle, left/right angle difference, and PSNR caused by positioning errors in panoramic X-ray imaging showed a strong correlation with image deformations. The total score of the K-means cluster analysis is a valid evaluation of the patient positioning for technologists in training.

Abbreviations

PSNR	Peak signal-to-noise ratio
DIR	Deformable image registration
DVF	Deformation vector field
ROI	Regions of interest
MAX	Maximum
MSE	Mean squared error

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Not applicable.

Author contributions

YT and SI conceived the idea of the study. YT developed the statistical analysis plan and conducted statistical analyzes. YT and NN contributed to the interpretation of the results. MH drafted the original manuscript. YT supervised the conduct of this study. All authors reviewed the manuscript draft and revised it critically on intellectual content. All authors approved the final version of the manuscript to be published.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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