RESEARCH ARTICLE

A new method to evaluate image quality of CBCT images quantitatively without observers

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Objectives: To develop an observer-free method for quantitatively evaluating the image quality of CBCT images by applying just-noticeable difference (JND).

Methods: We used two test objects: (1) a Teflon (polytetrafluoroethylene) plate phantom attached to a dry human mandible; and (2) a block phantom consisting of a Teflon step phantom and an aluminium step phantom. These phantoms had holes with different depths. They were immersed in water and scanned with a CB MercuRay (Hitachi Medical Corporation, Tokyo, Japan) at tube voltages of 120 kV, 100 kV, 80 kV and 60 kV. Superimposed images of the phantoms with holes were used for evaluation. The number of detectable holes was used as an index of image quality. In detecting holes quantitatively, the threshold grey value (ΔG), which differentiated holes from the background, was calculated using a specific threshold (the JND), and we extracted the holes with grey values above ΔG . The indices obtained by this quantitative method (the extracted hole values) were compared with the observer evaluations (the observed hole values). In addition, the contrast-to-noise ratio (CNR) of the shallowest detectable holes and the deepest undetectable holes were measured to evaluate the contribution of CNR to detectability.

Results: The results of this evaluation method corresponded almost exactly with the evaluations made by observers. The extracted hole values reflected the influence of different tube voltages. All extracted holes had an area with a CNR of ≥ 1.5 .

Conclusions: This quantitative method of evaluating CBCT image quality may be more useful and less time-consuming than evaluation by observation.

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Introduction

A close and important relationship exists between image quality and radiation dose. According to the “as low as

reasonably achievable” principle, it is important for both patients and operators to reduce radiation dose to the minimum level while maintaining sufficient image quality.^{1–4} The evaluation of image quality is an important factor in achieving radiation dose reduction because the use of poor-quality images obtained with reduced radiation doses may lead to misdiagnosis.

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Figure 1 (a) A Teflon plate phantom with holes of decreasing depths. (b) An overhead view of a Teflon plate phantom attached to a dry human mandible immersed in water.

Various methods and indices have been used to evaluate image quality.^{1–3,5–10}

The image quality of CBCT and CT machines is generally investigated with two different approaches: observer evaluation and evaluation using physical indices.^{1–3,5–10} Observer evaluation, often conducted with dry skulls and skull models, has the advantage of obtaining results reflecting clinical conditions and diagnoses. However, it is impossible to perform a standardized quantitative evaluation of image quality using these methods, because the observers and the test objects exhibit individual variations.^{1,2,8,9} Although some studies have used geometrical phantoms to achieve uniformity of the test objects, they have still used observers for evaluation. In addition, these experimental procedures are time-consuming and strenuous and yield variations under different display conditions.^{1,2,8,10–13}

Physical indices, such as spatial resolution and the contrast-to-noise ratio (CNR), have been used to evaluate image quality quantitatively.^{3,5–7,9} Although these physical indices are important, they cannot be directly related to clinical diagnostic accuracy. There are no methods that combine observer performance with physical indices to evaluate image quality. Therefore, it is important to develop a new system that requires no observers and uses standardized phantoms.

The standardization of display viewing conditions at clinical practices has been already established, and a specific threshold termed the just-noticeable difference (JND) is often used. The JND is the difference in luminance that the average observer can perceive in a given target under the same viewing conditions.¹⁴ In the evaluation of the image quality of intraoral radiography, applying JND to the images of a phantom could be an alternative quantitative method for evaluating observer performance.¹⁰ There have been, however, no studies on quantitative image quality evaluation for CBCT applying JND to phantom images. The development of a new quantitative method using phantoms and JND would be ideal for evaluating the image quality of CBCT, because it would not be influenced by different viewing conditions or observers.

The purpose of this study was to develop a new quantitative observer-free method of evaluating image

quality for CBCT by applying the JND to images of standardized phantoms.

Methods and materials

Test objects

Phantom for Experiment 1: Figure 1a shows a Teflon (polytetrafluoroethylene) plate phantom of 1-mm thickness, simulating bone. It has 12 columns, each with 7 holes. The diameter of each hole is 1 mm, and the depth of the seven holes in each column decreases from 0.7 mm to 0.1 mm from top to bottom. The phantom was attached to the molar region of a dry human mandible and immersed in water to simulate clinical conditions as closely as possible (Figure 1b).

Phantom for Experiment 2: Figure 2a shows an aluminium block phantom (to simulate teeth) and a Teflon block phantom (to simulate bone). Each phantom has 12 steps of 1-mm thickness and each step has 7 holes. The diameter of each hole is 1 mm, and the depth of the seven holes in each step decreases from 0.35 mm to 0.05 mm from top to bottom.^{15,16} We combined these two phantoms to make one block phantom, as seen in Figure 2b, and then immersed it in water.

These phantoms include different depths of holes with sharp edges as described above. The holes simulate small mass changes such as bone defects and caries with different volumes. We defined the number of detectable holes in the phantoms as the index of the image quality.^{15,16}

Image acquisition

Images were taken using a CB MercuRay CBCT system (Hitachi Medical Corporation, Tokyo, Japan).¹⁷ A preliminary experiment in which the surface with the holes was placed parallel to the X-ray beam revealed variations caused by the inherent limitations of CBCT; so, the surface with the holes was placed at right angle to the X-ray beam in the centre of the field of view,

Figure 2 (a) An aluminium step phantom and a Teflon step phantom, with holes of decreasing depths. (b) An overhead view of a block phantom, consisting of an aluminium step phantom and a Teflon step phantom.

a cube 51.2 mm on each side, after immersion in water. CBCT scans were obtained with 360° rotation during a 9.6-s exposure, with a reconstruction matrix of $512 \times 512 \times 512$ voxels; *i.e.* the calculated voxel size was 0.1 mm. The tube voltages were 120 kV, 100 kV, 80 kV and 60 kV, and the tube current was 15 mA.

Image analysis

The images were analyzed with ImageJ software (National Institutes of Health, Bethesda, MD).

Image samples

The number of detectable holes served as the index of the image quality; *i.e.* the image quality is better when more holes are detected. To measure the number of holes, the superimposed images of the phantom were reconstructed to simplify the evaluation of serial images. We reconstructed images in 0.1-mm intervals from the surface of the holes and then created three kinds of superimposition thicknesses: 1 mm, 0.3 mm and 0.1 mm (without superimposition) (Figure 3). We used these three images in Experiment 1 and the 0.3-mm thickness from the surface of the Teflon phantom in Experiment 2. All these images were adjusted to 8 bit, where the grey value of water was defined as 0.

Figure 3 (a) A serial image of a Teflon plate phantom attached to a dry human mandible. (b) A serial image reconstructed at 0.1-mm intervals from the surface of the holes. (c) An example of a 0.3-mm superimposed image.

Just-noticeable difference index

In our experiments, the number of detectable holes was calculated by using a JND index. The JND index is the input value to the greyscale standard display function, such that one step is a luminance difference in viewing conditions that the average observer can just perceive.¹⁴ The JND index is obtained using the following formula:

$$J(L) = 71.498068 + 94.593053 \times \log_{10}(L) + 41.912053 \times [\log_{10}(L)]^2 + 9.8247004 \times [\log_{10}(L)]^3 + 0.28175407 \times [\log_{10}(L)]^4 - 1.1878455 \times [\log_{10}(L)]^5 - 0.18014349 \times [\log_{10}(L)]^6 + 0.14710899 \times [\log_{10}(L)]^7 - 0.017046845 \times [\log_{10}(L)]^8, \quad (1)$$

where $J(L)$ is the JND index and L is the luminance (cd m^{-2}).

We measured the luminance of the monitor under the existing viewing conditions and obtained the JND index using Formula (1). Then, we converted the values to those corresponding to an 8-bit greyscale. These values served as just-noticeable greyscale difference (JNGD) values corresponding to the grey values of the background (Gb).

The threshold grey value (ΔG) which corresponded to the Gb of each step in the image was calculated using Equation (2).¹⁸

$$\Delta G = \sqrt{(JNGD)^2 + (SD)^2}, \quad (2)$$

where SD is the standard deviation of the background grey values, *i.e.* the noise of the image.

ΔG was rounded up to the nearest integer.

Extraction of holes

We first made superimposed images without noise by using a median filter (Figure 4a). We then made other images without holes by blocking out the holes using background density (Figure 4b). Then, hole-extracted images were created by subtracting the former images from the latter images (Figure 4c).

The detectable holes were defined as holes that showed a grey value $\geq \Delta G$ to the background with an

Figure 4 Extraction of holes: (a) a superimposed image without noise. (b) A superimposed image with holes blocked out using background density. (c) The hole-extracted image created by subtracting (a) from (b). (d) The detectable holes extracted using Find Foci.

area of $\geq 0.3 \text{ mm}^2$; the size of the area was decided by a preliminary experiment. The detectable holes in the hole-extracted images were extracted using Find Foci (<http://www.sussex.ac.uk/gdsc/intranet/microscopy/imagej/findfoci>), the plug-in of ImageJ (Figure 4d). The number of detected holes was tallied for every depth and was then defined as the extracted hole value for each depth.

Observer performance

In Experiment 1, the superimposed images (except for 80 kV) were displayed on a 19-inch liquid crystal screen (RDT195V; Mitsubishi Electric Corporation, Tokyo, Japan) in a dark room. Five oral and maxillofacial radiologists observed them and recorded the detectable holes. The number of detectable holes was averaged and tallied for each depth of hole in the same way and was defined as the observed hole value. We assessed the correlation between the extracted and observed hole values and determined the most suitable superimposition thickness. We also compared the effects of different voltages on the superimposed images at the most suitable thickness.

In addition, we measured the CNR of the shallowest detectable holes and the deepest undetectable holes in each step in both experiments to determine the threshold CNR value for detecting holes. The CNR was calculated using Equation (3).

$$\text{CNR} = \frac{\text{Gb} - \text{gray value of hole}}{\text{SD}}. \quad (3)$$

Statistical analysis was undertaken using the Wilcoxon signed-rank test with a p -value of 5%.

Results

Experiment 1: image analysis of a Teflon plate phantom attached to a dry human mandible

Figure 5 shows the relationship between the extracted hole values and the observed hole values. The values shown include all tested voltages. For every thickness, the extracted hole values and the observed hole values were closely related. Table 1 shows the indices of the average outliers of both values from the equation $y = x$. Because the value for the 0.3-mm superimposed images was the lowest, we decided to use these images for the rest of the experiments.

Figure 6 shows a comparison of the extracted hole values at four voltages for the 0.3-mm superimposed images. The values were higher in the deeper holes at every tube voltage, and increased as the voltage increased. Differences among the voltages were evident and were particularly clear in the shallower holes. There were significant differences between all pairs of voltages ($p < 0.05$), except for 120 kV and 100 kV ($p = 0.737$).

Figure 7 shows the average CNR of the shallowest detectable holes and the deepest undetectable holes in the 0.3-mm superimposed image. The average CNR of the shallowest detectable holes was higher than that of the deepest undetectable holes at all voltages. There was a significant difference between the shallowest detectable holes and the deepest undetectable holes

Figure 5 Relationships between the extracted hole values and the observed hole values in each superimposed image of a Teflon plate phantom attached to a mandibular bone. The values shown include all tested voltages. The extracted hole values and the observed hole values are closely related for every thickness.

($p = 0.0056$), and the threshold value between them was estimated to be 1.5.

Experiment 2: image analysis of a block phantom consisting of a combination of a Teflon step phantom and an aluminium step phantom

Having found that the 0.3-mm superimposed images reflected the observer evaluation most closely in Experiment 1, we used 0.3-mm superimposed images in Experiment 2.

Figure 8 shows a comparison of the extracted hole values at four voltages in the 0.3-mm superimposed images. The extracted hole values were higher in the deeper holes at every tube voltage and increased as the voltages increased, as seen in Experiment 1. There were significant differences between all pairs of voltages ($p < 0.05$), except for 120 kV and 100 kV ($p = 1$).

Figure 9 shows the average CNR of the shallowest detectable holes and the deepest undetectable holes. The average CNR of the shallowest detectable holes was higher than that of the deepest undetectable holes at all voltages. There was a significant difference between the shallowest detectable holes and the deepest undetectable holes ($p = 0.0005$), and the threshold value was estimated to be 1.5, as was seen in Experiment 1.

The extracted hole values of Experiments 1 and 2 were compared in the 0.3-mm superimposed images (Figure 10). The coefficient of determination was very high (0.93036) and therefore, we can say that the results of these analyses were very similar.

Discussion

In the evaluation of digital intraoral radiographic image quality, Yoshida *et al*¹⁰ showed in their study that JND

could be used as an alternative to observer evaluation. In this research, we evaluated the image quality of CBCT quantitatively by using JND and demonstrated that this method was more useful and less time-consuming than evaluation by observers.

In Experiment 1, we used a Teflon phantom attached to a mandibular bone immersed in water. This experimental setting, which included a high-density structure such as a mandibular bone, simulated conditions in clinical practice. Although in clinical practice we use serial images (*i.e.* three-dimensional images) of CBCT when making a diagnosis, in this experiment we reconstructed two-dimensional superimposed images to simplify the evaluation.

In Experiment 1, we first assessed our evaluation method using JND to see whether it could be used as a substitute for evaluation by observers. There was a good correlation between the extracted hole values and the observed hole values for every superimposed image. These findings confirmed that our image quality evaluation method could substitute for evaluation by observers. Yoshida *et al*¹⁰ indicated that this method could be used as an alternative for evaluation by observers in digital intraoral radiographic images, *i.e.* two-dimensional images. To apply this method to CBCT images (*i.e.* three-dimensional images), we reconstructed two-dimensional superimposed images. Our results were consistent with those of Yoshida *et al*;¹⁰ thus, the use of superimposed images for image evaluation has been validated.

In our research, five oral and maxillofacial radiologists evaluated the image samples. This raises the question that the results might have been different if we had used more observers, including non-radiologists. Yoshiura *et al*^{18,19} developed a method to evaluate the quality of digital intraoral radiographic systems with a test object containing holes with different depths. This methodology is similar to ours, but they used more observers, including general dentists, radiological technologists and nurses. Their results showed a good

Table 1 The index of the average outliers from the equation “ $y = x$ ” in each superimposed image

Thickness (mm)	1	0.3	0.1
Index	0.842	0.317	0.653

Figure 6 Comparison of the extracted hole values at four voltages in the 0.3-mm superimposed images of a Teflon plate phantom attached to a mandibular bone. The values are higher for the deeper holes at every tube voltage, and increase as the voltages increase. There are significant differences between all pairs of voltages ($p < 0.05$), except for 120 kV and 100 kV ($p = 0.737$).

correlation between observer performance and calculated values from the threshold based on contrast and noise, irrespective of the wide range of diagnostic ability of their observers. This was partly because detecting holes does not require specialized knowledge of image interpretation. Therefore, it is highly likely that we would obtain similar results with an increased number of observers, regardless of their level of training.

Since outliers were at a minimum in the 0.3-mm superimposed images, we used these images for the

Figure 7 Comparison of the average contrast-to-noise ratio (CNR) of the shallowest detectable holes and the deepest undetectable holes in the 0.3-mm superimposed images of a Teflon plate phantom attached to a mandibular bone. There are significant differences between the shallowest detectable holes and the deepest undetectable holes ($p = 0.0056$), and the threshold value between them is estimated to be 1.5.

Figure 8 Comparison of the extracted hole values at four voltages in the 0.3-mm superimposed images of a block phantom, consisting of a Teflon step phantom combined with an aluminium step phantom. The values are higher in the deeper holes at every tube voltage, and increase as the voltages increase, as seen in Figure 6. There are significant differences between all pairs of voltages ($p < 0.05$), except for 120 kV and 100 kV ($p = 1$).

subsequent quantitative evaluation. This finding also indicated that superimposed images with a certain thickness could be applied to the substitution for evaluating serial images.

We next assessed the extracted hole values of four voltages in the 0.3-mm superimposed images to evaluate

Figure 9 Comparison of the average contrast-to-noise ratio (CNR) of the shallowest detectable holes and the deepest undetectable holes in the 0.3-mm superimposed images of a block phantom, consisting of a Teflon step phantom combined with an aluminium step phantom. There is a significant difference between the shallowest detectable holes and the deepest undetectable holes ($p = 0.0005$), and the threshold value between them is estimated to be 1.5, as seen in Figure 7.

Figure 10 Relationship between the extracted hole values in Experiment 1 and those in Experiment 2 in the 0.3-mm superimposed images. The coefficient of determination is very high (0.93036).

the influence of different voltages on hole detection. The values increased at high voltages in the superimposed images, and this tendency was particularly marked in the shallower holes. This finding also showed that minute changes should be measured when evaluating the influence of voltages.

There was no significant difference in the extracted hole values between 120 kV and 100 kV ($p = 0.737$). This result was contradictory because the image quality is often better at higher voltages. Because an image intensifier was used as a detector of the CBCT system (CB MercuRay), our findings could reflect a characteristic of an image intensifier with a narrow dynamic range.

In Experiment 2, we used a block phantom, consisting of a Teflon step phantom combined with an aluminium step phantom. According to the results of Experiment 1, we used 0.3-mm superimposed images

from the surface of the Teflon phantom. The extracted hole values in the superimposed images were affected by differences in the voltage. The extracted hole values of Experiments 1 and 2 were also compared in the 0.3-mm superimposed images, and these results were very similar. The results of Experiment 2, in which we used only phantoms with no variable factors, suggested that it would be possible for us to develop quantitative image quality evaluation for CBCT without observers.

In addition, the average CNR of the shallowest detectable holes and the deepest undetectable holes for each step was measured in both experiments. CNR is a major factor in physical image quality and is often measured to compare various kinds of machines or to evaluate the influences of scanning conditions.^{1-3,5-10} There was a significant difference between the average CNR of the shallowest detectable holes and the deepest undetectable holes in both experiments, and the threshold value between them was estimated to be 1.5. In other words, we could identify the holes in a certain area with a CNR of ≥ 1.5 in CBCT observation. Our method is useful because it is easier than measuring the CNR of all holes one by one in the phantom.

We did not analyze spatial resolution as a physical index in this study. It also remains unclear whether or not our method reflects actual diagnostic performance. However, our method allows extrapolation to detect bone defects or the mandibular canal in clinical diagnosis. A further study on the correlation between our new method and diagnostic performance is needed before it can be applied to clinical practice.

In conclusion, this image quality evaluation method involving the application of JND to CBCT images of standardized phantoms could be used as a convenient method for quantitatively evaluating different scanning conditions. It could be considered as an alternative to time-consuming evaluation by observers.

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