RESEARCH ARTICLE

Prediction of detectability of the mandibular canal by quantitative image quality evaluation using cone beam CT

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Objectives: To compare the results of a new quantitative image quality evaluation method that requires no observers with the results of receiver operating characteristic (ROC) analysis in detecting the mandibular canal (MC) in cone beam CT (CBCT) images.

Methods: A Teflon (polytetrafluoroethylene) plate phantom with holes of different depths was scanned with two CBCT systems. One CBCT system was equipped with an image intensifier (Experiment 1), and the other was equipped with a flat panel detector (Experiment 2). Holes that were above the threshold gray value (ΔG), calculated using just-noticeable difference (JND), were extracted. The number of extracted holes was used as the index of the image quality, and was compared with the Az values calculated by ROC analysis to detect the MC.

Results: The number of extracted holes reflected the influence of different scanning conditions, and showed a strong correlation with the Az values calculated by ROC analysis. Indices of the number of extracted holes corresponding to high Az values for detecting the MC were obtained in both experiments.

Conclusions: Our image quality evaluation method applying JND to images of a standardized phantom is a quantitative method that could be useful for evaluating the detectability of the MC in CBCT images.

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Introduction

Evaluation of the location of the mandibular canal (MC) is important before treatment such as implant placement or extraction of an impacted tooth in the mandibular molar region. It is important to measure the distance from the MC to the alveolar crest and the buccal and lingual aspects of the alveolar bone to avoid damage to the inferior alveolar nerve and vessels located in the

MC.¹⁻⁶ Cone beam CT (CBCT) can display important anatomical structures as three-dimensional images with high resolution, allowing them to be measured accurately.⁷⁻⁹ To make an accurate diagnosis, it is essential to use images with sufficient image quality.

Receiver operating characteristic (ROC) analysis is one method for evaluating the diagnostic accuracy of medical diagnostic systems.^{10,11} ROC analysis evaluates not only the physical characteristics of the images, but also the psychological factors of the observers. The

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diagnostic accuracy of known systems is compared with ROC curves to indicate the relationship between the false-positive rate and the true-positive rate associated with changes in the observers' criteria.

We have developed a new method to evaluate the image quality of CBCT images quantitatively without observers, applying the concept of just-noticeable difference (JND) to images of phantoms taken using a CBCT system.¹² Phantoms with sharply-defined holes of differing depths were fabricated; the holes simulated small mass changes such as bone defects with different volumes.^{13,14} The number of detectable holes in the images of the phantoms was used as the index of image quality. The results of this evaluation method corresponded almost exactly with the evaluations by observers,¹² and the number of extracted holes reflected the influence of different scanning conditions. However, it remained unclear whether or not our method reflected actual diagnostic performance.¹²

When detecting the MC, we perceive the contrast created by small mass changes to the surrounding bone trabeculae. Our evaluation method with phantoms containing holes should be closely related to detecting the MC in that both are dependent on the detection of small mass changes. Although one previous study investigated the detectability of the MC in CBCT using ROC analysis with observers,¹⁵ no studies have developed a quantitative evaluation method without the use of observers.

The purpose of this study was to test whether our quantitative evaluation method, applying JND to the images of phantoms with simulated bone, could be extrapolated to assess diagnostic image quality to detect the MC in CBCT images.

Methods and materials

Test objects

A 1 mm thick Teflon (polytetrafluoroethylene) plate containing 84 holes was used as a phantom to simulate bone. The plate had 12 columns, each with 7 holes. The diameter of each hole was 1 mm, and the depth of the holes in each column decreased from 0.7 to 0.1 mm from top to bottom (Figure 1a).¹² The phantom was attached to the molar region of a dry human mandible

Figure 1 (a) The Teflon plate phantom with holes of different depths. (b) An overhead view of the Teflon plate phantom attached to a dry human mandible.

(Figure 1b), and was immersed in water to simulate clinical conditions as closely as possible. The holes simulated small mass changes such as bone defects with different volumes. The number of detectable holes was defined as the index of the image quality. The phantom was scanned with two CBCT systems.

Half mandibles without a Teflon phantom were also scanned to evaluate the detectability of the MC.

Image acquisition

Experiment 1: Images were scanned using a CB MercuRay CBCT system (Hitachi Medical Corporation, Tokyo, Japan)¹⁶ with an image intensifier as a detector. Test objects were placed at right angles to the X-ray beam in the center of the field of view. The size of the field of view was a cube with side length of 51.2 mm. CBCT scans were obtained during a 9.6 s exposure, and the reconstruction matrix was $512 \times 512 \times 512$ voxels, i.e. the calculated voxel size was 0.1 mm. The tube voltages were 120, 100, 80 and 60 kV, and the tube current was 15 mA.

Experiment 2: Images were obtained using a CS 9300C Select CBCT system (Carestream Health Inc., Marne-la-Vallée, France) with a flat panel detector. Test objects were placed as in Experiment 1. The scanning range was 100×50 mm (diameter $\times$ height). CBCT scans were obtained during a 6.1 s exposure, and the calculated voxel size was 0.18 mm. Three dry half mandibles of different sizes were used. We performed this experiment in two steps: Step 1, using almost equal exposure doses (90 kV/5 mA, 70 kV/10 mA and 60 kV/15 mA) to evaluate the influence of tube voltages; and Step 2, using the same tube voltage (70 kV) with different tube currents (15, 10, 5 and 2 mA) to evaluate the influence of tube currents.

Image analysis of the Teflon phantom

The images were analyzed with ImageJ software (National Institutes of Health, Bethesda, MD). Superimposed images from the surface with holes were used for evaluation. The number of detectable holes served as the index of image quality, i.e. the image quality is better when more holes are detected. Having found that the 0.3 mm superimposed images reflected the observer performance and could evaluate image quality quantitatively,¹² we used 0.3 mm superimposed images in Experiment 1. In Experiment 2, we resliced the phantom images by 0.09 mm because of the 0.18 mm voxel size of the CBCT system, and the images were then superimposed as 0.27 mm thickness (close to 0.3 mm as in Experiment 1). In detecting the holes, the threshold gray value (ΔG), which differentiated the holes from the background, was calculated using JND. The extracted holes were defined as holes which had gray values above ΔG (Figure 2). The number of extracted holes was tallied and used as the index of the image quality. For Experiment 1, the data

Figure 2 The detectable holes of the superimposed images were extracted using ImageJ software.

of the number of extracted holes were retrieved from our previous study.¹²

ROC analysis on the detectability of the MC

Using thin metal wire as markers, the MC was divided into four equal parts from the posterior margin of the mental foramen to the anterior margin of the mandibular foramen. Markers numbered 1, 2 and 3 from anterior to posterior (Figure 3) corresponded approximately to the position of the first, second and third molars, respectively, to evaluate the MC in each region.

The images were analyzed with ImageJ software. The images of each half mandible were rotated so that the MC became horizontal at each marker, and coronal images were reconstructed. An average of 145 slices (14.5 mm) of serial coronal images were reconstructed at each marker, and the images were cropped with and without the MC using a region of interest (ROI) of 8 × 8 mm for observation (Figure 4). The ROI without MC was selected in the region of sponge bone so as to avoid the MC and minimize the area of cortical bone included.

The cropped images were displayed randomly on a personal computer (MB-T900B; MouseComputer Co., Ltd., Tokyo, Japan) in a dark room. Four oral and maxillofacial radiologists observed and assessed them to see if they could detect the MC or not, using a 5-point

Figure 3 A half mandible with thin metal wire markers. The MC was divided into four equal parts. MC, mandibular canal.

scale (“definitely without MC” = 1, “probably without MC” = 2, “cannot assess” = 3, “probably with MC” = 4 and “definitely with MC” = 5). ROC analysis was performed with ROCKIT (Charles E Metz, University of Chicago, IL), and the effects of different scanning conditions with different tube voltages were compared with the area under the curve (Az value).

We performed ROC analysis in Experiment 1, scanning four dry half mandibles of different sizes, including the mandible used in the Teflon phantom experiment. For Experiment 2, the ROC analysis data were retrieved from our previous study on the detectability of the MC in a CS 9300C Select CBCT system.¹⁵ In this previous study, the ROC analysis divided the visibility of the MC into two groups (“clear” and “unclear”).

The number of extracted holes in the Teflon phantom experiment was compared with the Az value from the ROC analysis in Experiments 1 and 2.

Results

Experiment 1: relationship between the detectability of the MC and the number of extracted holes under different tube voltages

Figure 5 shows ROC curves obtained from observation under different tube voltages. The vertical axis indicates the true positive fraction, and the horizontal axis indicates the false positive fraction.^{10,11} Table 1 shows the Az values for each voltage. The Az values increased as the voltage increased. The number of extracted holes obtained in our previous study¹² and the Az values were compared (Figure 6), and a high correlation coefficient was found (0.94849).

Experiment 2: relationship between the detectability of the MC and the number of extracted holes under almost equal exposure dose, and under different tube currents

Tables 2 and 3 show the average number of extracted holes at three almost equal exposure doses (Table 2), and at four different tube currents (Table 3). The average number of extracted holes increased as the voltage increased, and also as the tube current increased.

The number of extracted holes and the Az values of clear (Figure 7a) and unclear (Figure 7b) MCs obtained in the previous study¹⁵ were compared. The Az values obtained under almost equal exposure dose and under different tube currents are plotted together in each graph. The correlation coefficient was high for both clear (0.88775) and unclear (0.92515) MCs as seen in Experiment 1.

The number of holes and the Az value increased under better scanning conditions in both Experiments 1 and 2. In particular, images with more than 70 extracted holes corresponded almost exactly with the Az values of more than 0.8.

Figure 4 An example of cropped images at each marker: (a) without the MC and (b) with the MC. MC, mandibular canal.

Discussion

We examined the detectability of the MC using our method, which evaluates the image quality of CBCT images quantitatively without observers, by applying the concept of JND to images of a Teflon phantom simulating bone. In ROC analysis, “non-diseased” and “diseased” images are generally randomly displayed to observers for evaluation.^{10,11} Images without the MC

were considered to be “non-diseased”, and images with the MC were considered to be “diseased” in this study.

In Experiment 1, the Az values increased as the voltage increased. This result supports the findings of Jasa *et al*¹⁵. We next assessed the correlation between the number of holes obtained from our previous study and the Az values from the ROC analysis. A high correlation coefficient was found, suggesting that it would be possible to predict the detectability of the MC under different tube voltages by using our quantitative evaluation method applying JND to images of the Teflon phantom simulating bone without the use of observers.

In Experiment 2, the number of extracted holes increased as both parameters increased, reflecting the influence of different scanning conditions. We also investigated a correlation between the number of extracted holes and the Az values obtained in the previous study. As in Experiment 1, a high correlation coefficient was found. This result could be interpreted to mean that our quantitative evaluation method could predict the detectability of the MC, regardless of the different CBCT systems or scanning conditions employed.

When more than 70 extracted holes were detected, the Az values were almost all over 0.8 in both

Figure 5 Receiver operating characteristic (ROC) curves under different tube voltages in Experiment 1.

Table 1 Az values obtained in Experiment 1

Tube voltage (kV)	120	100	80	60
Az value	0.832	0.796	0.794	0.722

Figure 6 Relationship between the number of extracted holes obtained in our previous study and the Az values in Experiment 1. A high correlation coefficient was found (0.94849).

Experiments 1 and 2. This suggests that the number of extracted holes over 70 could be used as an index of the detectability of the MC. In Experiment 2, which used a CBCT system equipped with a flat panel detector as an advanced detector, the Az values were close to 1.0 in clear MCs, and mostly over 0.8 in unclear MCs. We recognized that it was possible to detect most MCs when more than 70 extracted holes were detected. However, the Az values of the unclear MCs were lower than those of the clear MCs, although the same number of extracted holes was recorded. Therefore, we should determine the appropriate number of extracted holes depending on the object being diagnosed. In the case of unclear MCs, the appropriate number of extracted holes may be over 75, because higher voltages and currents are required to detect unclear MCs as reported by Jasa *et al*¹⁵ in their previous study.

However, in Experiment 1, which used a CBCT system equipped with an image intensifier as an older type detector, the Az value corresponding to images with approximately 70 extracted holes was around 0.8. This Az value was lower despite tube voltages that were much higher than those in Experiment 2. This may be a result of the inferior quality of the image intensifier, which has a narrow dynamic range compared with the flat panel detector. Additionally, these values were similar to those of the unclear MCs scanned with the flat panel detector. Although individual differences or the number of samples may have influenced this result, it could be considered that we observed the

Table 2 Average number of extracted holes obtained under almost equal exposure doses in Experiment 2

Parameter	90 kV/5 mA	70 kV/10 mA	60 kV/15 mA
Number of extracted holes	76.3	74	72

Table 3 Average number of extracted holes obtained under the same tube voltage (70 kV) and different tube currents in Experiment 2

Tube current (mA)	15	10	5	2
Number of extracted holes	75.7	71	69	62.7

MCs scanned with an image intensifier under similar contrast to the unclear MCs scanned with a flat panel detector.

The usefulness of our evaluation method using different CBCT systems was unclear in our previous study, but this point has been clarified in the present study. Additionally, our quantitative evaluation method employing the holes to simulate small mass changes could be applied to evaluate not only MCs, but also bone defects or caries in clinical situations. Weerawanich *et al*¹⁷ developed a new image quality evaluation method that had a higher correlation with observer performance with several cut-off values; however, its relationship to diagnostic performance is still unclear. Although the number of cut-off values (threshold gray value or ΔG) in this method is limited, we confirmed that diagnostic performance was reflected in the number of extracted holes. Thus, our method is simpler than Weerawanich's method.¹⁷

There are many comparative studies about diagnostic performance using ROC analysis with several kinds of objectives, while changing scanning conditions or systems.^{15,18–22} ROC analysis is affected by these factors but it eventually derives the result as “diagnostic accuracy”. In this study, therefore, we evaluated the correlation of Az values with the number of extracted holes, which is the final output of our evaluation method. We did not analyze the influence of individual factors of scanning conditions such as tube voltages, tube currents and spatial resolution, or different objectives. A further study investigating the correlation between the Az values and the number of extracted holes under different scanning conditions and objectives is needed to increase the reliability of predicting diagnostic

Figure 7 Relationship between the number of extracted holes and the Az values obtained in our previous study in Experiment 2: (a) correlation with clear MC images and (b) correlation with unclear MC images. Both correlation coefficients were high: (a) 0.88775 and (b) 0.92515. MC, mandibular canal.

performance with our quantitative evaluation method using JND.

Conclusion

Our image quality evaluation method applying JND to images of a standardized Teflon phantom could be useful as a quantitative technique to assess diagnostic image quality to evaluate the detectability of the MC in CBCT images.

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