ORIGINAL ARTICLE

Oral Radiology

Computer-aided measurement of mandibular cortical width on dental panoramic radiographs for identifying osteoporosis

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Abstract

Aim: To develop a computer-aided diagnosis system to continuously measure mandibular inferior cortical width on dental panoramic radiographs and evaluate the system's efficacy in identifying postmenopausal women with low-skeletal bone mineral density.

Methods: Mandibular inferior cortical width was continuously measured by enhancing the original X-ray image, determining cortical boundaries, and evaluating all distances between the upper and lower boundaries in the region of interest. The system's efficacy in identifying osteoporosis at the lumbar spine and the femoral neck was evaluated for 100 women (≥50 years): 50 in the development of the tool and 50 in its validation.

Results: The sensitivity and specificity of the cortical measurements for identifying the development patients were 90% (95% confidence interval shown in parentheses) (63.0–87.0) in women with low spinal bone mineral density, and 81.8% (70.1–91.8) and 69.2% (56.2–81.8) in those with low femoral bone mineral density, respectively. Corresponding values in the validation patients were 93.3% (85.9–100) and 82.9% (71.4–92.7) at the lumbar spine, and 92.3% (84.5–99.5) and 75.7% (63.0–87.0) at the femoral neck, respectively.

Conclusion: Our new computer-aided diagnosis system is a useful procedure in triage screening for osteoporosis.

Introduction

Osteoporosis is a skeletal disorder characterized by low bone mass and micro-architectural deterioration, with a resulting increase in bone fragility and susceptibility to fracture.[1] Because 70% of bone strength is determined by skeletal bone mineral density (BMD) and the remaining 30% by factors determining bone quality, such as bone turnover rate, BMD measurement of the general skeleton is an important indicator of risk of fractures for individuals. Menopause is a major risk factor for osteoporosis, and most postmenopausal women are at risk of osteoporosis and consequent fractures.[2] Osteoporosis poses a global health burden.[3–5] Osteoporotic fractures contribute to increased medical costs and incremental risks of morbidity and mortality. In particular, osteoporotic hip fractures are strongly correlated with an increased risk of mortality and a decreased quality of life.[5] In 1990, 26% of all hip fractures occurred in Asia, and this rate is projected to rise to 37% in 2025 and to 45% in 2050.[5] However, a recent study indicated a clear decline in the number of hip fractures in the USA after 1995.[6] Improved screening strategies for osteoporosis and the use of bisphosphonates, approved after 1996 by the Food and Drug Administration in the USA, are considered major reasons for this phenomenon.[6] This clearly indicates that the early detection of individuals at risk of osteoporotic fractures and early intervention can help reduce the incidence of these fractures, especially hip fractures.

In Japan, the estimated number of individuals at risk of osteoporotic fractures is approximately 120 million, of whom approximately 90% are postmenopausal women.[7] However, only 4.6% of elderly Japanese women who visit health centers are examined for osteoporosis, which implies that the patients are not interested in clinical follow up.[8] A new screening strategy for determining the risk of osteoporotic fractures in postmenopausal women is needed to reduce the number of osteoporotic fractures in Japan, as well as in other countries, where the number of osteoporotic fractures continues to increase.

Measuring the mandibular inferior cortical width (MCW) below the mental foramen of the mandible on dental panoramic radiographs might be a useful method for identifying postmenopausal women with low-skeletal BMD or at risk of osteoporotic fractures. Many investigators have manually measured the MCW in the previous studies.[9–12] In two studies, a computer-aided technique was developed, in which the MCW was semiautomatically measured, and manual assistance was needed during some parts of the measurement.[13,14] Furthermore, the MCW was measured at only one point (below the mental foramen) in most previous studies. In addition, the hyoid bone image might overlap the cortex below the mental foramen and influence the MCW measurement. These limitations need to be addressed while determining BMD with accuracy.

The objectives of this study, therefore, were to develop a computer-aided (CAD) system that continuously measures the MCW between the upper and lower boundaries of the cortical bone in the region of interest (ROI), and to evaluate the diagnostic efficacy of this system in identifying postmenopausal women with low-skeletal BMD.

Materials and methods

Patients

A total of 531 women underwent a skeletal BMD examination at an oral radiology clinic at Hiroshima University Hospital (Hiroshima, Japan) between 1996 and 2001. This study comprised 100 postmenopausal women, of whom 50 were allocated to the development of the tool and 50 to its validation. The inclusion criteria were postmenopausal women aged 50 years and older, with no previous diagnosis of osteoporosis. Dental panoramic radiographs were taken for all the patients after informed consent was obtained. The exclusion criteria were: (a) women who had menstruated less than 1 year prior to the study, or had undergone hysterectomy or oophorectomy; (b) women with a history of a metabolic bone disease (hyperparathyroidism, hypoparathyroidism, Paget's disease, osteomalacia, renal osteodystrophy, or osteogenesis imperfecta), cancer with bone metastasis, significant renal impairment, bone destructive lesion (e.g., malignant tumors or osteomyelitis) of the mandible, and spinal fracture (confirmed semiquantitatively on lateral radiographs); and (c) women on medication that affects bone metabolism (e.g., estrogen) or smokers.

Bone densitometry

All 100 women underwent BMD of the lumbar spine (L2–L4) and femoral neck by dual-energy X-ray absorptiometry (DXA) (DPX-alpha; Lunar, Madison, WI, USA). The patients were classified as normal (*T*-score: ≥ -1 standard deviation [SD]), osteopenic (*T*-score: -1 to -2.5 SD), or osteoporotic (*T*-score: ≤ -2.5 SD) at each skeletal site according to the World Health Organization (WHO) criteria.[15] Since the Adult Health Study cohort in Japan[16] reported that the cut-off BMD value of osteoporosis in the lumbar spine based on the Japanese definition[17] (less than 70%) was similar to that based on the WHO definition (*T*-score: ≤ -2.5 SD), we used the WHO definition in this study.

Dental panoramic radiography

All the panoramic radiographs were obtained using AZ-3000 (Asahi, Kyoto, Japan) at 12 mA at 15 sec; kVp values varied between 70 and 80, and were digitized at a resolution of 300 dpi using a flat-bed scanner (ES-8000; Epson, Tokyo, Japan). Screens of speed group 200 (HG-M; Fuji Photo Film, Tokyo, Japan) and film (UR-2; Fuji Photo Film) were used. One set of duplicate films (MI-Dup; Fuji Photo Film) processed with an automatic film processor (Cepros M; Fuji Photo Film) comprised 100 original panoramic radiographs for the assessment. The appearance of the mandibular inferior cortex was clear bilaterally in the radiographs. The Hiroshima University Human Subject Committee approved the study protocol.

Digital panoramic radiography for a pilot study

This study also included digital panoramic radiographs by randomly selected 40 participants as for the pilot study. We applied our CAD system to pairs of a digital dental panoramic radiograph and a redigitized dental image of its print on film to evaluate the diagnostic validity.

Automated system development for MCW measurements

The schematic diagram of the proposed automated system describes how to determine the ROI, enhance the

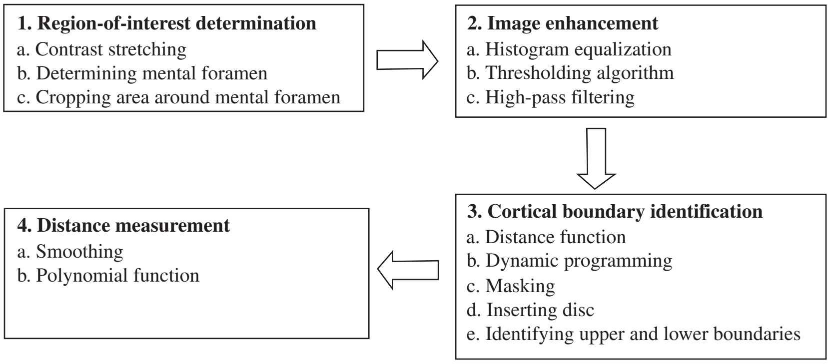

Figure 1. Schematic diagram of continuous cortical width measurement.

original image, detect the inner and outer boundaries of the cortex, and finally measure the distance between the boundaries of the cortex (Figure 1). This system was run on a Pentium [R] Dual-core (CPU 2.50 GHz) with 2 GB RAM.

ROI determination

The mental foramen is an opening on the lateral part of the mandible, inferior to the second premolar. The area (300 × 300 pixels) involved in the lower border of the mandibular cortex below the mental foramen cropped manually on the right and left sides was considered as the ROI (Figure 2). However, the area around the mental foramen is disturbed by a low contrast and dark color. Therefore, it is important to improve the contrast of an image by ''stretching'' the range of intensity values that it contains, in order to span a desired range of values, to the corresponding area. Selecting the ROI is useful for simple and fast computing, because the original radiograph has a resolution of 1744 × 3158 pixels.

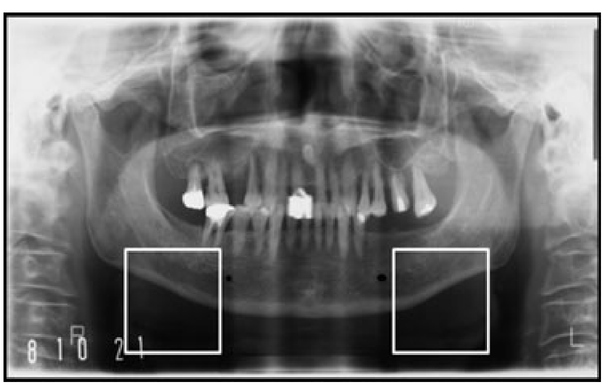

Figure 2. Digitized dental panoramic radiographs showing two boxes corresponding to the regions of interest between the mental foramen and the angle of the mandible on the right and left sides of the mandible.

Image enhancement

The enhancement process provides better inputs for automated image-processing techniques. The typical histogram equalization method is the first step in image enhancement to obtain new enhanced images with a uniform histogram. The usual method of thresholding is to separate

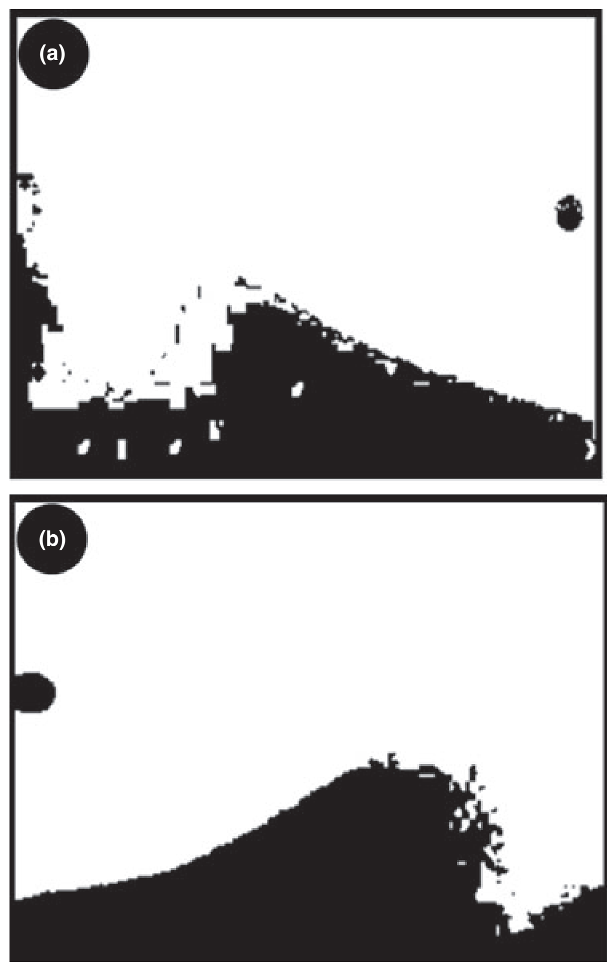

Figure 3. Binary images of the right (a) and left (b) cortices.

the object pixel values greater than a specified threshold value as the foreground, and those lesser than this threshold value as the background. Pixel values less than 10% and greater than 90% in the histogram are not considered because of variations in background illumination and the presence of the area corresponding to the teeth and label text on each image.

We applied a clustering thresholding algorithm[18] to separate the image pixels into the foreground and background, where threshold determination is based on intraclass and interclass variances of the pixel values. This procedure generated binary images with the determined ROI (Figures 3a and 3b). Multiplying this binary image with the original image of the desired ROI generates an image that removes the background and preserves all gray levels considered as the foreground.

The final step of applying high-pass filtering[19] works well at sharpening the boundary along the cortical bone. Since direct application of high-pass filtering on the multiplied image of the previous step suppressing or eliminating some small features, average filter (low-pass filter) is used to generate the low-frequency image. The resultant low-frequency image is then subtracted from the original image that leads to the high frequency image. This resultant grayscale image is binarized using a threshold related to the mean value of all the pixels in the image (Figures 4a and 4b).

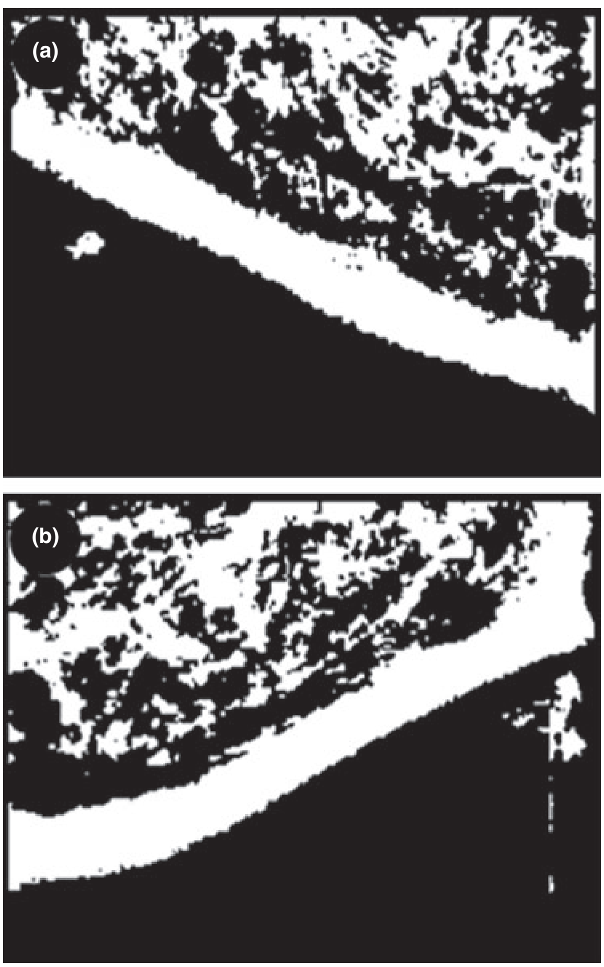

Figure 4. High-pass filter images of the right (a) and left (b) cortices.

Cortical boundary identification

The cortical boundaries of the mandibles are unclear because of multiple connections with the trabecular bone. In this study, we used image-processing techniques[20] based on the eight neighborhood distance functions (ENDF) to estimate the cortical width. The ENDF at each pixel represents the distance from the pixel to the boundary as the pixel value (Figures 5a and 5b). The trace of maximum pixel values represents the medial axis of the cortical bone. This trace is obtained by dynamic programming.[21] Figures 5c and 5d shows the trace obtained by applying the dynamic programming method from left to right. The cortical boundaries are finally obtained as the envelope of the disc, which is located at each pixel on the trace, whose diameter equals the pixel value (Figures 5e and 5f).

Distance measurement

The last step involves measuring the distance between the upper and lower boundaries of the cortical bone. In

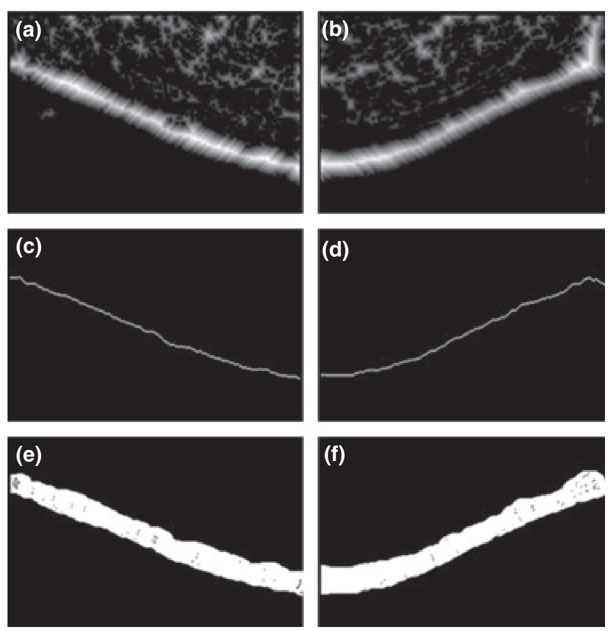

Figure 5. Right and left sides of the mandibular cortical bone. Eight neighborhood distance functions (ENDF) (a and b); dynamic programming (c and d); disc insertion (e and f).

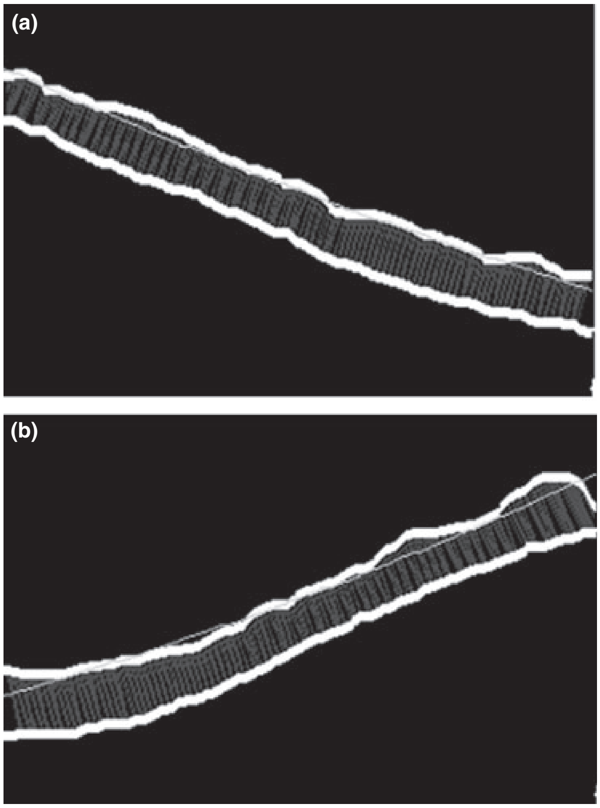

Figure 6. Smoothing and polynomial images of the right (a) and left (b) cortices.

order to determine the direction of the measurements, a second-order polynomial function is fitted to the upper boundary using the least squares method.[20] The cortical width at each point is measured along the line tangent to the polynomial curve, which approximates the upper boundary (Figures 6a and 6b).

In the present study, the results of the continuous measurement were summarized by the trimmed mean, which excludes 10% of the highest and lowest data. This mean value is considered to be an estimate of the cortical width.

Statistical analyses

The mean of the MCW on both sides of the mandible was used in this study. Pearson's correlation coefficient was calculated to evaluate the correlations between the mean MCW measured by this system and the BMD of the lumbar spine and femoral neck for 50 postmenopausal women. A receiver-operating characteristic (ROC) curve analysis was used to determine the optimal cut-off thresholds of the MCW measured by our system for identifying patients with low-skeletal BMD (osteopenia and osteoporosis). The risk-index range corresponding to a sensitivity of approximately 90% was chosen to determine the optimal cut-off threshold. The sensitivity, specificity, positive predictive values, negative predictive values, accuracy, and likelihood ratio for the positive results for identifying patients with low BMD were calculated on the basis of this optimal cut-off threshold. The area under the ROC curve (AUC) was also calculated to evaluate the diagnostic efficacy of MCW in identifying patients with low-skeletal BMD. We conducted statistical analyses for two possible errors in the proposed system. The first one was inter- and intra-examiner errors caused by the manual setting of the ROI, which was the only manual operation in this system. The second was caused by the positioning shift at capturing panoramic radiographs. In order to evaluate these two errors, we used 10 pairs of radiographs, in which each one was taken for the same patient at a 1-month interval. It was experimentally proved that the inter- and intra-examiner errors caused by the manual setting of the ROI were negligibly small. Similarly, the error by positioning shift was evaluated by comparing the measurements on the different radiographs of the same patients, which were taken at a 1-month interval by one examiner. Technical error measurements (TEM) and systematic errors (SE) were calculated by comparing the measurements between the two examiners on the same radiographs for evaluating inter-examiner errors and two measurements on the same radiographs by one examiner for evaluating intra-examiner errors with Dahlberg's formula[22] and paired *t*-test,[23] respectively, at a significance level of 5%.[24]

Results

The optimal cut-off thresholds for the MCW were 19.4 pixels for the lumbar spine and 19.6 pixels for the femoral neck in identifying women with low BMD for the development patients (Table 1). At this recommended

Table 1. Number of patients with normal and low-skeletal bone mineral densities (BMD) of mandibular cortical width among the development and validation patients

Mandibular cortical width	Development patients		Validation patients	
	Normal	Low	Normal	Low
Lumbar spine BMD				
≤Cut-off threshold	10	9	6	14
>Cut-off threshold	30	1	29	1
Femoral neck BMD				
≤Cut-off threshold	12	9	9	12
>Cut-off threshold	27	2	28	1

Cut-off threshold for cortical width at lumbar spine: 19.4 pixels, and at femoral neck: 19.6 pixels.

Table 2. Diagnostic efficacy of automatic measurements of the mandibular cortical widths for identifying women with low-skeletal bone mineral densities (BMD) in the development and validation patients at the 95% confidence interval

Identification site	Sensitivity (%)	Specificity (%)	Positive predictive value (%)	Negative predictive value (%)	Accuracy (%)	Likelihood ratio (+), %
Development patients						
Lumbar spine	90.0 (81.7–98.3)	75.0 (63.0–87.0)	47.4 (33.2–60.8)	96.8 (90.6–100)	78.0 (75.7–88.3)	3.6 (2.3–4.9)
Femoral neck	81.8 (70.1–91.8)	69.2 (56.2–81.8)	42.9 (29.3–56.7)	93.1 (85.9–100)	72.0 (59.6–84.5)	2.7 (1.5–4.6)
Validation patients						
Lumbar spine	93.3 (85.9–100)	82.9 (71.4–92.7)	70.0 (57.3–82.7)	96.7 (90.6–100)	86.0 (76.4–95.6)	5.4 (4.0–6.7)
Femoral neck	92.3 (84.5–99.5)	75.7 (63.0–87.0)	57.1 (43.3–70.7)	96.6 (90.6–100)	80.0 (68.9–91.9)	3.8 (2.5–5.1)

Table 3. Diagnostic efficacy of automatic measurements of the mandibular cortical widths for identifying women with combined skeletal bone mineral densities (BMD) among the development and validation patients at the 95% confidence interval

Patients	Sensitivity (%)	Specificity (%)	Positive predictive value (%)	Negative predictive value (%)	Accuracy (%)	Likelihood ratio (+), %
Development	90.5 (83.8–95.1)	70.9 (61.4–79.0)	45.2 (35.6–54.8)	96.6 (92.0–100)	75.0 (65.7–82.4)	3.1 (2.3–4.1)
Validation	92.9 (86.2–96.5)	77.8 (68.9–84.9)	61.9 (52.2–70.9)	96.6 (92.0–100)	82.0 (73.3–88.3)	4.2 (3.3–5.2)

threshold value, the sensitivity and specificity of identifying development patients with low BMD were 90% (95% confidence interval [CI]: 81.7–98.3) and 75% (95% CI: 63.0–87.0), respectively, at the lumbar spine, and 81.8% (95% CI: 70.1–91.8) and 69.2% (95% CI: 56.2–81.8) at the femoral neck, respectively. The corresponding values in the validation patients were 93.3% (95% CI: 85.9–100) and 82.9% (95% CI: 71.4–92.7) at the lumbar spine, and 92.3% (95% CI: 84.5–99.5) and 75.7% (95% CI: 63.0–87.0) at the femoral neck, respectively (Table 2). The AUC for identifying development patients with low spinal BMD and femoral neck BMD were 0.8100 (95% CI: 0.722–0.875) and 0.7600 (95% CI: 0.667–0.833), and those for the validation patients were 0.8650 (95% CI: 0.791–0.922) and 0.8300 (95% CI: 0.744–0.891), respectively. In addition, the optimal cut-off threshold for the combination of data of both the lumbar spine and femoral neck for identifying women with low BMD in the development patients was 19.6 pixels. At this threshold value, the sensitivity and specificity of identifying development patients with low BMD were 90.5% (95% CI: 83.8–95.1) and 70.9% (95% CI, 61.4–79.1), respectively. The corresponding values in the validation patients were 92.9% (95% CI: 86.9–96.9) and 77.8% (95% CI: 69.1–85.2), respectively (Table 3). In the pilot study, we found significant correlations between the digital radiographs and redigitized radiographs ($r = 0.66$, $P < 0.001$) when screening for osteoporosis. Inter- and intra-examiner reliability results calculated for the manual setting of ROI for the TEM are shown in Table 4. This study found that all the r values of TEM for inter- and intra-examiners were almost 1.0, which is in accordance with the suggested cut-off.[24] It was also found that there was no statistically-significant systematic error for inter- and intra-examiners, and none of the measurements showed an error greater than 2%. An analysis of the positioning errors with different radiographs showed the r values of TEM and SE at almost 1.0 and less than 1%, respectively.

Table 4. Inter and intra-examiner reliability for manual setting of regions of interest for relative technical error measurement (TEM) results (Dahlberg's formula)

Measurement (cortical width)	TEM	r
First month		
Inter-examiner	0.052	0.998
Intra-examiner	0.050	0.999
Second month		
Inter-examiner	0.095	0.993
Intra-examiner	0.055	0.999

r, coefficient of reliability.

Discussion

The sensitivity and specificity of our CAD system were high among both the development and validation patients for identifying postmenopausal women with low-skeletal BMD. The AUC of this system for the same patients was almost ≥0.8, indicating that the diagnostic efficacy of the system in identifying postmenopausal women with low-skeletal BMD was moderate. In our previous study, which used data from the same 100 patients,[18] the sensitivity and specificity were approximately 88% and 56–59%, respectively. These clearly indicate that the diagnostic efficacy of our new system is better than that of the old system, especially in terms of specificity. The practice of measuring MCW below the mental foramen of the mandible has been widely used worldwide from the time investigators[25,26] simultaneously reported it to be the most appropriate site for determining MCW. However, the hyoid bone image sometimes overlaps the cortex below the mental foramen on dental panoramic radiographs, which can result in measurement errors with CAD systems, such as the one used in our previous study.[18] It is likely that continuous measurements of the MCW between the mental foramen and the angle of the mandible with our new CAD system could reduce such measurement errors. Furthermore, the specificity of identifying postmenopausal women with low-skeletal BMD, based on the manual measurements used in the previous study,[9] was approximately 60%, although the sensitivity was almost 90%. This also indicates the possibility that continuous measurements of the MCW improve the diagnostic efficacy of the CAD system, relative to one-point measurements (e.g., below the mental foramen).

Several investigators have developed simple decision rules based on a questionnaire, such as the Osteoporosis Screening Tool (OST), to identify women with low-skeletal BMD or osteoporosis.[27–30] The sensitivity of such decision rules in identifying postmenopausal women with osteoporosis ranged from 92% to 95%, and the specificity ranged from 35% to 46%.[29] The sensitivity of our current CAD system was almost the same, but the specificity was much higher. The difference in these results is reasonable, because the CAD system directly assesses the bones on radiographs. The OST uses parameters, such as age and weight, which might change among the time of the measurement. Also, the optimal cut-off threshold might be different among postmenopausal women in different countries. However, the MCW directly reflects the general skeleton. Further, the average time required for the measurements of the MCW was only 9 s.

Significant correlations were observed in the development patients between MCW and lumbar spine BMD ($r = 0.56$, $P < 0.001$) and femoral neck BMD ($r = 0.51$, $P < 0.001$) in the current study. Arifin *et al.*[18] reported significant correlations between MCW values obtained using their CAD system below the mental foramen of the mandible. El Maghraoui *et al.*[31] recently evaluated the association between skeletal BMD measured by DXA and broadband ultrasound attenuation (BUA) values measured by quantitative ultrasound (QUS) of the heel, which is widely used in the screening of osteoporosis, in 295 asymptomatic postmenopausal women. They found that BUA correlated weakly with total hip BMD ($r = 0.36$) and lumbar spine BMD ($r = 0.32$), and even less with femur BMD ($r = 0.30$), although all of the correlations were significant ($P < 0.01$). Lappa *et al.*[32] also evaluated the association between QUS and general skeletal BMD in 123 postmenopausal Caucasian women, and reported that the most significant correlation was observed between BUA and femoral neck BMD in postmenopausal women aged 66–77 years ($r = 0.626$, $P < 0.01$). Dey *et al.*[33] found significant correlations between total hip BMD and the metacarpal index ($r = 0.48$, $P < 0.001$) when screening for osteoporosis in 379 elderly, community-dwelling women aged 75 years and older. A comparison of our results with those of previous studies indicated that our CAD system might be a useful screening tool for osteoporosis.

The use of digital dental panoramic radiography is expected to spread rapidly worldwide in the near future. The digitization of the analog film did not have any influence on the MCW measurement, which was proven in the pilot study. It is also proven that our CAD system can also accurately utilize digital dental panoramic radiographs for identifying groups at high risk of osteoporosis. The Aichi Dental Association, Nagoya, Japan conducted a large clinical trial in which 95% of women aged 50 years and older, who were identified by their general dental practitioners on the basis of incidental findings from dental panoramic radiographs, actually had osteopenia or osteoporosis.[34] We compared the MCW measured by our CAD system with the digital dental panoramic radiographs taken at a1-month interval of 10 randomly-selected 10 patients. We found some differences between the measurements in the average width and SD of the cortical bone, which were less than one and two pixels, respectively. This can be due to the positioning error or magnification effect. One of the limitations of this study was the relatively small number of patients (50 postmenopausal women), and also the fact that the patients were relatively healthy postmenopausal women based on the rigid exclusion criteria. A second limitation was that optimal cut-off thresholds for the MCW might be different for different types of dental panoramic machines, and also the optimal cut-off thresholds for the MCW might be different for other populations. We have not experienced much distortion in our measurement system. However, we experienced some irremovable noises or objects in the continuous measurements of cortical width, which might influence the measurement of the MCW. Thus, we have adopted a trimmed mean method in our study to remove the false values caused by uneven illumination and other local noises. However, the accuracy that we obtained in this system was highly acceptable and relatively more robust to the single-point measurement. Currently, we are focusing on utilizing the continuous measurements for achieving more robust diagnoses with statistical data analyses. However, it can easily be extended to graphical formats to depict BMD by introducing new software for converting the numerical measurement to graphics.

The use of our CAD system by general dental practitioners might allow them to identify many patients with low-skeletal BMD and refer these patients to medical professionals for further examination. Additional studies with a large number of postmenopausal women would be necessary to overcome this system limitation. In conclusion, the sensitivity and specificity of our new CAD system in identifying postmenopausal women with low-skeletal BMD were relatively higher than those obtained in previous studies. Our new CAD system is a useful tool in screening for osteoporosis.

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