Original article

Use of experimental phantoms to determine the accuracy and reliability of mandibular cortical width measurements by panoramic radiography and cone-beam computed tomography

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Abstract: The present study used an aluminum phantom to calculate accurate vertical magnification values around the mental foramen on panoramic radiography (PR) and compared corrected PR (Cor-PR) thickness measurements of the aluminum phantom and mandibular cortical width (MCW) of the human head with cone-beam computed tomography (CBCT) measurements at two fields of view (FOVs). The calculated vertical magnification value for PR around the mental foramen was 1.37. Measurements of the aluminum phantom significantly differed between Cor-PR and CBCT with an FOV of 100 mm and between CBCT with FOVs of 40 and 100 mm; however, MCW measurements did not significantly differ among the three methods. There was a very strong correlation between Cor-PR and CBCT with an FOV of 40 mm and between CBCT with FOVs of 40 mm and 100 mm, and intraobserver and interobserver agreement was good-to-excellent for all methods. These results suggest that Cor-PR and CBCT with small and large FOVs are acceptable for measuring MCW.

Keywords: cone beam tomography, mandibular cortical width, mental index, osteoporosis, panoramic radiography

Introduction

Osteoporosis is a systemic skeletal disorder characterized by decreased bone mineral density that increases the risk of pathological bone fracture [1]. Osteoporosis is associated with 8.9 million pathological fractures of the hip, vertebrae, forearm, and other bones worldwide [2]. Osteoporosis prevalence is linked to age, and the condition is more common in women. Because 200 million adults have osteoporosis worldwide, it is an important public health concern [3]. In Japan, 27% of the population is 65 years or older, and the country has the highest rate of aging in the world (population aged ≥65 years as a percentage of total population. The World Bank [https://data.worldbank.org/indicator/SP.POP.65UP.TO.ZS] accessed on July 28, 2019), over 13 million adults are affected with osteoporosis in Japan (Orimo H., the guidelines for prevention and treatment of osteoporosis 2015 edition., 1-14. Life Science Publishing, Tokyo, Japan, 2015 [in Japanese]). Therefore, the number of pathological bone fractures in persons with osteoporosis (osteoporotic fracture) is expected to increase markedly in Japan [4]. Osteoporotic fractures in older adults significantly decrease their quality of life and increase expenses associated with the required medical and nursing care. Hence, early detection, diagnosis, and intervention before osteoporotic fracture are crucial [5].

Radiographic examinations such as dual-energy absorptiometry (DXA) and quantitative computed tomography (qCT) have been used to diagnose osteoporosis and quantify bone loss by calculating bone mineral density (BMD). DXA is the gold standard for diagnosis of osteoporosis and prediction of osteoporotic fracture [5] but is not used as a screening tool [6]. Quantitative ultrasoundography is most commonly used in Japan to screen for osteoporosis.

Several findings, measurements, and indices on panoramic radiography (PR), one of the most common imaging modalities in dentistry, are used as possible indicators of osteoporosis or osteopenia [6]. Klemetti et al. [7] and Taguchi et al. (Taguchi A et al., Diagnosis of postmenopausal osteoporosis by panoramic radiographs. J Jpn Soc Bone Morphom, 4, 113-118, 1994 [in Japanese]) examined the height of the inferior cortex below the mental foramen on the PR, the so-called mandibular cortical width (MCW), or mental index. This index was introduced as a tool to detect bone mineral loss and is one of the most reliable indices to triage individuals with previously undetected osteoporosis or osteoporosis [6,8]. Many reports have shown a correlation of MCW with sex, age, disease stage, and post-therapeutic improvement [9-13]. However, MCW measurements obtained with PR require magnification correction. Dutra et al. [14] reported that correction of the magnification factor for individual PR units yielded the highest concordance of MCW between actual thickness and PR measurements. Calcioari et al. [15] reported that magnification occurring with PR is a limitation when the values are used to derive some mandibular indices. The authors suggested that accurate magnification correction of PR units might improve the accuracy of mandibular indices and allow rigorous multicenter comparison of PR measurements of MCW.

Cone-beam CT (CBCT) is widely used in dentistry. Although PR is used around the world to measure MCW and other mandibular indices when assessing osteoporosis and other conditions associated with decreasing skeletal BMD [6], some studies used CBCT to measure MCW and mandibular indices [16-18]. Koh and Kim [16] found no correlation between MCW measured on cross-sectional CBCT images and bone density. In contrast, Brasilheiro et al. [17] reported a significant correlation of MCW measured on cross-sectional CBCT with bone density and concluded that CBCT indices, including MCW on cross-sectional CBCT, may be useful for identifying postmenopausal women with previously undetected low skeletal BMD. A recent study [18] compared MCW measured on cross-sectional CBCT images with MCW on panoramic images reconstructed with CBCT datasets and on PR images collected from healthy volunteers. The use of tomographic images reconstructed in different planes was valid as the gold standard to measure MCW. However, no study has examined differences in values obtained on CBCT with small and large fields of view (FOVs).

The present study aimed to calculate accurate magnification correction values for the PR unit in the department and to compare these corrected PR measurements to measurements acquired on CBCT with small and large FOVs.

Materials and Methods

This study comprised measurement of vertical magnification around the mental foramen in PR, with an aluminum phantom for correction, and comparison of thickness measurements of the aluminum phantom and MCW of human head phantoms with corrected PR values (Cor-PR) and CBCT measurements with small and large FOVs.

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A cylindrical phantom (Fig. 1A-D; Mushroom model X001-9951-4, Morita, Kyoto, Japan) consisting of a mandibular condyle and mandibular fossa made of 1-mm-thick aluminum embedded in acrylic was used. The hemisphere-shaped mandibular fossa was 20 mm in diameter. The height and diameter of the bullet-shaped mandibular condyle were 20 mm and 10 mm, respectively (Fig. 1B-D). The cylindrical phantom was rotated by 90°, and the bullet-shaped mandibular condyle was set parallel to the dental arch at the mandibular molars of a printed full-size axial CT image of the mandible on a flat table made of plastic. A line connecting both edges of the hemisphere-shaped mandibular fossa of the phantom was positioned through the distal edge of the left mandibular canine on the axial CT image. Figures 2 and 3 show the relationship between the aluminum phantom and the virtual mandible. The phantom was then fixed by tape on the CT image onto the flat table.

Three human head phantoms (PH series, Kyoto Kagaku, Kyoto, Japan; SH-1 Sanwa Kaseihin, Osaka, Japan), i.e. dry human skulls embedded in acrylic resin, were used for PR and CBCT imaging.

Image acquisition

Panoramic radiography

PR imaging was performed (Veraviewepoc X550, Morita) under the following conditions: tube voltage, 75 kV; tube current, 10 mA; normal panorama mode; and exposure time, 17.2 s. The manufacturer indicated that the vertical magnification error was 130%. A storage photostimulated phosphor (PSP) plate (15 × 30 mm) in a cassette (DirectView GP, Carestream Health, Rochester, NY, USA) was used for imaging.

The cylindrical phantom on the table was set on a chin rest unit corresponding to the mandibular position in reference to the axial CT image of the mandible on the same table (Fig. 2). A laser beam was set at midline of the CT image of the mandible, and the anteroposterior position was set at the lateral edge of the hemisphere-shaped mandibular fossa by using another laser beam (Fig. 2). After image acquisition, the image was digitized with a DirectView CR system 850, and the image data were stored in a server. The pixel size on the digitized PR image was 100 × 100 µm. An aluminum plate mimicking the mandibular condyle and mandibular fossa embedded in acrylic resin (gray area) was used for imaging. A storage photostimulated phosphor (PSP) plate (15 × 30 mm) in a cassette (DirectView GP, Carestream Health, Rochester, NY, USA) was used for imaging.

CBCT imaging (3D Accuitomo F17D, Morita) was performed under the following conditions: tube voltage, 90 kV; tube current, 5 mA; 360° scan; and exposure time, 17.5 s. Images were acquired at two FOVs: 40 mm and 100 mm.

For the 40-mm FOV acquisition, the cylindrical phantom on the flat table was set on the chin rest unit of the CBCT corresponding to the mandibular position. The axis of rotation was set at the center of the phantom with an FOV of 40 mm (Fig. 3). When imaging with an FOV of 100 mm, the laser beams of the unit were set through the midline, the edge of the maxillary central incisors, and both sides of the mandibular first molar.

The axis of rotation of CBCT imaging with an FOV of 40 mm was set at the apical area of the mandibular premolar of the human head phantom, after ensuring that the Frankfort horizontal plane was parallel to the floor. When imaging with the 100-mm FOV, the laser beams were set through the midline, the edge of the maxillary central incisors, and both sides of the mandibular first molar.

The acquired CBCT datasets were reconstructed (i-View workstation ver. 2.01; Morita) and stored in an image server. The length on one side of the isotropic voxels of the reconstructed CBCT images was 80 µm for an FOV of 40 mm and 250 µm for an FOV of 100 mm.

Measurement of the thickness of the aluminum phantom

The thickness of the aluminum phantoms on PR was measured (SDS-DICOM Viewer, Nobori, Tokyo, Japan) at the medial, central, and distal points on the upper and lower cortex of the straight segment of the bullet-shaped mandibular condyle (Fig. 4A). On cross-sectional CBCT images that were vertical to the axis of the bullet-shaped mandibular condyle, the thickness of the aluminum phantoms of the straight segment of the bullet-shaped mandibular condyle were measured at the medial, central, and distal points on the upper and lower cortex (Fig. 4B). The thickness of aluminum phantoms was measured three times by
The thickness of the aluminum phantom was measured at points a-f on a straight segment of the upper and lower cortex of the bullet-shaped mandibular condyle. Before evaluation, the observers were calibrated by using other PR and CBCT images to clarify the starting and end points for measuring the thickness of aluminum phantoms. The starting and end points were defined as the most superior and most inferior borders, respectively, of the cortex of the aluminum phantoms. The mean of the measurements was recorded for each imaging modality. The vertical magnification value on PR, i.e. the ratio of measurements on PR and the actual thickness of the cortex at the upper and lower cortex of the bullet-shaped mandibular condyle (1 mm), was calculated by using the following formula: Vertical magnification of PR = PR measurement value/thickness of bullet-shaped mandibular condyle.

The Cor-PR measurements corrected for vertical magnification by the value derived from measurements with the cylindrical phantom were compared with measurements acquired with CBCT at different FOVs.

MCW Measurement

On PR images, both sides of the MCW were measured by using the method of Taguchi et al. [19]. To measure MCW on CBCT, cross-sectional images that were vertical to the dental arch were reconstructed on an i-View workstation (Fig. 5A). An image through the center of the mental foramen was selected on both FOV datasets. MCW on cross-sectional CBCT images was measured three times by each of the three observers using a previously described method [18], as shown in Fig. 5B. Before evaluation, the observers were calibrated by using other RP and CBCT images to clarify the starting and end points for measuring MCW. The starting and end points for measuring were defined as the most superior and most inferior borders, respectively, of the mandibular inferior cortex. The mean of MCW measurements for each modality was recorded. Cor-PR measurements (corrected for vertical magnification by values derived from measurements with the cylindrical phantom) and CBCT measurements at both FOVs were compared.

Statistical analysis

Normality of measurements and homoscedasticity among measurements in each experiment were confirmed with the Kolmogorov-Smirnov test and Mauchly sphericity test, respectively. Repeated one-way analysis of variance (ANOVA) was used to compare thickness values of the phantoms among Cor-PR, CBCT with an FOV of 40 mm, and CBCT with an FOV of 100 mm. The paired r-test with Bonferroni correction was used for post hoc testing if significant differences were detected on prior repeated ANOVA. Pearson coefficients were calculated for the correlation between values from Cor-PR and CBCT with an FOV of 40 mm and values from CBCT with FOVs of 40 mm and 100 mm. A Pearson r of <0.30 was defined as a very weak or no correlation. Similarly, 0.30 ≤ r < 0.49, 0.50 ≤ r < 0.69, 0.70 ≤ r < 0.89, and 0.90 ≤ r ≤ 1.00 were defined as weak, moderate, strong, and very strong correlations, respectively (Estimating Analytical Errors Using Regression Statistics; Westgard QC [http://www.westgard.com/lesson44.htm] accessed on July 28, 2019). Intraobserver and interobserver agreement of measurements was evaluated by intraclass coefficients (ICC). In accordance with the work of Koo and Li [20], ICC values were interpreted as follows: values of <0.5, 0.50-0.75, 0.75-0.90, and >0.90 indicated poor, moderate, good, and excellent reliability, respectively. All statistical analyses were performed with commercial software (SPSS Statistics for Windows, version 25.0, IBM, Armonk, NY, USA). A P value of <0.05 was considered to indicate statistical significance.

Results

The means for measurements of the aluminum phantom by PR, CBCT with an FOV of 40 mm and CBCT with an FOV of 100 mm were 1.37 (95% confidence interval [95% CI]: 1.33-1.41), 0.98 (95% CI: 0.91-1.04), and 1.08 (95% CI: 1.02-1.13), respectively (Table 1). The vertical magnification value for PR of the mental foramen was 1.37, and the mean Cor-PR was 1.00 mm (95% CI: 0.97-1.03). The measurements were distributed normally (P > 0.05), and homoscedasticity of the measurements of aluminum phantom thickness was confirmed (P > 0.05). Post hoc testing revealed significant differences between Cor-PR and CBCT with an FOV of 100 mm (P = 0.034) and between CBCT with an FOV of 40 mm and CBCT with an FOV of 100 mm (P = 0.006). However, no significant difference was found between Cor-PR and CBCT with an FOV of 40 mm (P > 0.05).

The means for MCW measurements by PR, CBCT with an FOV of 40 mm, and CBCT with an FOV of 100 mm were 5.77 mm (95% CI: 5.21-6.33), 4.35 mm (95% CI: 3.80-4.89), and 4.45 mm (95% CI: 3.92-4.50), respectively (Table 2). The value for Cor-PR was 4.22 mm (95% CI: 3.81-4.63). MCW measurements were distributed normally (P > 0.05), and homoscedasticity of MCW measurements was confirmed (P > 0.05). Repeated one-way ANOVA showed no significant differences in measurements by Cor-PR, CBCT with an FOV of 40 mm, and CBCT with an FOV of 100 mm (P > 0.05). The Pearson r values for the correlation between Cor-PR and CBCT with an FOV of 40 mm and between CBCT with CBCT with FOVs of 40 mm and 100 mm were 0.905 (P = 0.013) and 0.945 (P = 0.005), respectively, indicating very strong correlations. Intraobserver and interobserver reliability in measuring MCW was good-to-excellent (Table 3).
Discussion

The present findings indicate that the vertical magnification value for PR can be easily obtained with an aluminum phantom and that it slightly differed from the value provided by the manufacturer. This suggests that accurate correction of vertical magnification is necessary before attempting comparison of linear measurements on one PR unit to those on another PR unit. The small difference between the present vertical magnification on PR and the manufacturer’s value suggests that calculating accurate vertical magnification on PR may be of limited clinical significance. However, magnification in PR units varies from 115% to 130% [21]. Bozdag et al. [21] reported that use of crude global magnification values did not allow for correction of magnification and distortion of specific regions on PR images. They emphasized the need for correction by accurate vertical magnification in the region of interest on PR images. They also suggested that use of global magnification values on PR is inappropriate for correction of linear measurements of local structures on such images, as described by Dutra et al. [14].

Comparison of thickness measurements for the aluminum phantom by Cor-PR, CBCT with an FOV of 40 mm, and CBCT with an FOV of 100 mm showed that values were significantly higher for CBCT with an FOV of 100 mm than for the other methods. Voxel size in CBCT with an FOV of 100 mm was more than twice that when the FOV was 40 mm. A thickness of 1 mm was estimated to be only four voxels at an FOV of 100 mm. Thus, the small number of voxels could fluctuate by sampling error. Moreover, irregular trabecular morphology connected to the mandibular cortex may be associated with inaccurate CBCT measurements. Additionally, trabecular bone tails and endosteal cortical residues, might partially explain errors in PR measurements [6]. On CBCT measurements of MCW, angle setting to the occlusal plane, to obtain cross-sectional CBCT images, might affect the reliability of CBCT measurements. Moreover, irregular trabecular morphology connected to the mandibular cortical morphology, such as trabecular bone tails and endosteal cortical residues, might partially explain errors in PR measurements [6].

Table 1 Thickness (mm) of the straight segment of the bullet-shaped mandibular condyle, by imaging method

| Measurement point | PR | Cor-PR | CBCT FOV = 40 mm | CBCT FOV = 100 mm |
|-------------------|----|--------|-----------------|-------------------|
| Point a           | 1.38 | 1.04 | 1.08 | 1.15 |
| Point b           | 1.36 | 0.99 | 0.98 | 1.04 |
| Point c           | 1.40 | 1.02 | 0.97 | 1.14 |
| Point d           | 1.30 | 0.95 | 0.91 | 1.03 |
| Point e           | 1.42 | 1.04 | 0.99 | 1.06 |
| Point f           | 1.35 | 0.99 | 0.92 | 1.03 |
| Mean              | 1.37 | 1.00 | 0.98 | 1.08 |

Table 2 Mandibular cortical width (mm), by imaging method

| Measurement point | PR | Cor-PR | CBCT FOV = 40 mm | CBCT FOV = 100 mm |
|-------------------|----|--------|-----------------|-------------------|
| Phantom 1 R       | 6.51 | 4.75 | 5.13 | 5.15 |
| Phantom 1 L       | 6.06 | 4.42 | 4.57 | 4.8 |
| Phantom 2 R       | 5.64 | 4.12 | 3.81 | 3.93 |
| Phantom 2 L       | 6.07 | 4.43 | 4.56 | 4.42 |
| Phantom 3 R       | 5.00 | 3.65 | 3.78 | 3.84 |
| Phantom 3 L       | 5.44 | 3.97 | 4.22 | 4.57 |
| Mean              | 5.79 | 4.22 | 4.35 | 4.45 |

Table 3 Reliability in measuring mandibular cortical width, by imaging method

| Number of observers | PR FOV = 40 mm | CBCT FOV = 40 mm |
|---------------------|---------------|-----------------|
| Intraobserver reliability | 0.986 | 0.984 | 0.932 | 0.999 | 0.773 | 0.708 |
| Interobserver reliability | 0.695 | 0.807 | 0.861 |

PR, panoramic radiography; CBCT, cone-beam computed tomography; FOV, field of view; ICC, intraclass coefficient.
caused by differences in the thickness of the sites measured. The purpose of measuring MCW with each method was to assess the reliability of the methods to potentially detect osteoporosis or osteopenia. The MCW cutoff on PR to distinguish a pathologic decrease in skeletal BMD is unclear. In a review of previous studies, Calciolari et al. [15] reported that the cut-off value for osteoporosis diagnosis was 2.69 to 5.00 mm. Therefore, future studies should use aluminum phantoms with a thickness of 2 to 3 mm to evaluate measurement validity. Second, MCW measurement was performed manually. Several researchers have used automatic measurement of MCW, and good agreement was reported between studies using automatic and manual measurement of MCW on PR [24]. In addition, the present results showing good reliability for measurements of MCW with all methods also support the validity of manual measurement of MCW on PR and CBCT. Automated MCW measurement would be useful for screening a population. However, this method has some limitations in obtaining accurate values when the superior border between the cortex and trabecular bone is not precisely detected because of an indistinct margin [24]. In addition, because of the small number of phantoms used, the clinical implications of the present findings are limited. Future studies should compare the reliability of MCW measurements among methods by using mass clinical datasets with methods based on those used in this study. The vertical magnification value for PR may be suitable for all populations if the same PR unit is used. The aluminum phantom was set to correspond to the dental arch on a CT image at the level of mandible. The vertical magnification of the MCW can probably be changed because mandible width varies among individuals. Therefore, in clinical settings, a reference index depicted on PR images might be useful in calculating actual MCW. The present study limited its focus to the MCW index and did not address linear PR measurements of other mandibular indices, such as gonial index, anterogonial index, and panoramic mandibular index [6,15], which are not reliable in measurements and were reported to be unsuitable for osteoporosis screening [6]. Therefore, the present study used MCW on PR, which is widely accepted as one of the most reliable indicators for detecting osteoporosis and osteopenia [6].

In conclusion, the present study used phantoms to examine methods to correct vertical magnification when measuring MCW on PR. The vertical magnification value of the PR unit used in the hospital was 137% around the mental foramen. Although the clinical usefulness is limited, the Cor-PR value for MCW was similar to MCW measured on CBCT. The present results suggest that Cor-PR and CBCT with small and large FOVs are acceptable for measuring MCW.

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Conflict of interest
The authors declare no conflict of interest.

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