Basic research on experimental jawbone phantom: Bone mineral density measurement for jawbones using quantitative computed tomography

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Abstract

Abstract: Jawbone quality is an important factor that affects implant prognosis, and preoperative diagnosis of bone quality is considered significant to assess the predictability of implant treatment. In this study, an experimental jawbone phantom was created and used in quantitative computed tomography (QCT) to accurately measure bone mineral densities (BMDs). Then an examination was performed on the effects of scanning conditions on measured values.

In clinical practice, the experimental jawbone phantom will be placed near the patient’s jawbone. Thus, this phantom was shaped in an arch form to be compatible with the jawbone morphology. This phantom contained apatite rods with the following known BMDs used as references: 0, 50, 100, 150, and 200 mg/ml. Another jawbone phantom, a reference phantom, was used as a standard, scanned with the experimental phantom, and then used for calibration. Its reference BMDs were 75 and 125 mg/ml. These phantoms were used to examine how the measured values were affected by (1) the height and (2) the left and right positions of the target when scanning the reference phantom and (3) the tilting when scanning the experimental phantom.

Results: A regression line was plotted using the HU value of each apatite area of the experimental phantom and using the apatite values of relevant areas of the reference phantom. The R² was 0.9997, indicating a strong correlation. When BMDs were calculated from the HU values of the reference phantom using the regression line, the densities were 76.2 mg/ml at the 75-mg/ml site and 127.6 mg/ml at the 125-mg/ml site, indicating close values (p>0.05). When the center of the scan of the reference phantom was moved maximally 5 cm upward and downward, the measured value was 78.2 ± 0.3 mg/ml and 72.9 ± 1.1 mg/ml, respectively, at the 75-mg/ml site. There was no significant difference between 75 mg/ml and these values (p>0.05). When the center of the scan of the reference phantom was moved maximally 5 cm to the right and left, the value was 81.6 ± 2.2 mg/ml and 81.2 ± 14.6 mg/ml, respectively, at the 75-mg/ml site. There was no significant difference between 75 mg/ml and these values (p>0.05). When the experimental phantom was rotated maximally 45° toward the right and left, both values were 76.2 ± 1.1 mg/ml at the 75-mg/ml site, indicating no significant difference between 75 mg/ml and these values (p>0.05). When the experimental phantom was tilted at 15° increments relative to the long axis, the value was 77.9 ± 16.1 mg/ml at 15° and 78.9 ± 16.4 mg/ml at 30°, indicating significantly higher values relative to that at 0° (p<0.05).

Discussion and Conclusion: There was no significant difference in the measured apatite amounts when the experimental phantom was rotated 45° relative to the reference phantom and when the center of the scan was moved approximately 5 cm from the reference phantom. These results suggested the possibility that the apatite amount at any jawbone site can be accurately obtained using the HU values. That is, the results suggested that there will be no major effect on the bone quality diagnosis even if a subject moves from the correct position during the CT scan. However, when the experimental phantom was tilted anteriorly and posteriorly relative to the long axis, the measured value with no tilting differed significantly from the measured values with tilting of 15° and 30°. Thus, one must take care to avoid tilting when scanning and be cautious when securing the experimental phantom because errors in measured values can easily occur if it is tilted.

The results of this study suggested the effectiveness of this experimental jawbone phantom to measure the BMD at any site of a patient’s jawbones. However, when placing the experimental phantom on the patient’s jawbone, one must take caution to ensure that the phantom’s long axis is perpendicular to the CT-slice plane. The results also suggested that if the patient position moves during scanning, the measured values do not change to such an extent as to greatly affect the diagnosis of bone quality.

Key words: QCT (Quantitative Computed Tomography), bone density measurement for jawbones, CT values, dental implants
I. Introduction

In 1972, Hounsfield presented the technology of computer tomography (CT) at the annual meeting of the Radiological Society of North America. This technology has been applied not only in medicine for imaging of the brain and the whole body but also in dentistry for implant treatment, which began in the late 1980s mainly in Europe and the U.S.1 In preoperative CT examinations for implants, the most important element is the ability to provide information on the three-dimensional state of jawbones, which is necessary for preoperative diagnosis.2-3 CT imaging is a method that can produce tomographic images of a human body through a process described as follows. The body to be imaged is placed between an x-ray tube and an opposing, highly sensitive detector, and the x-ray beams are emitted from multiple directions. Linear absorption coefficients of a human body are obtained and converted into CT values, which are processed by a computer to reconstruct an image. Jawbone quality, which is diagnosed using these CT values, is an important factor affecting the prognosis of implant treatment, and a preoperative examination of bone quality is considered significant to assess the predictability of implant treatment. Quantitative computed tomography (QCT) enables one to distinguish between cortical bone and trabecular bone and is considered to be effective in the diagnosis of jawbones because it enables bone mineral density (BMD) measurement in an area.4-6 In QCT, however, calibration phantoms are designed for lumbar spine and femur and are not suitable for measurement of jawbones. In addition, a method has not yet been established to evaluate quantitatively the bone quality at the implant placement site, and there are still many unclear points regarding the relationship between the bone quality and fixation of an implant in the initial stage.

The purpose of this study was to create an experimental jawbone phantom used in QCT for accurate measurement of jawbone BMDs and to examine the effects of scanning conditions on measured values.

II. Methods

In clinical practice, the experimental jawbone phantom will be placed near the patient’s jawbone. Thus, this phantom was shaped in an arch form to be compatible with the jawbone morphology. This phantom contained apatite rods with the following known BMDs used as references: 0, 50, 100, 150, and 200 mg/ml. Another jawbone phantom, a reference phantom, was used as a standard, scanned with the experimental phantom, and then used for calibration. Its reference BMDs were 75 and 125 mg/ml (Fig. 1). These phantoms were used to examine how the measured values were affected by the height, left and right positions, and tilting when scanning the experimental phantom. The CT scanner used was a Lemage Supreme CT (GE Yokogawa Medical Systems, Ltd.). The scanning conditions were 140-kV tube voltage, 160-mA tube current 160, 1-mm slice thickness, 1-mm/sec table feed, 1-sec/slice scan time, 0.5-mm reconstruction interval, and edge reconstruction kernel. The standard scan direction was along the long axis of the

(Fig. 1) Experimental jawbone phantom and reference jawbone phantom

(Fig. 2) Measured cross-section during CT scanning

(Fig. 3) Center of the scan of the reference jawbone phantom

(Fig. 4) The center of the scan was moved maximally 5 cm upward and downward at 1 cm increments and was moved maximally 5 cm to the right and left at 1 cm increments during the scanning of the reference jawbone phantom. The experimental jawbone phantom was rotated maximally 45° to the right and left at 15° increments and tilted maximally 30° at 15° increments relative to the long axis.
phantom (Fig. 2). The standard center of the scan was established as the upper border of the 75-mg/ml site (Fig. 3). The phantom was scanned, the obtained DICOM images were transferred to the Advantage Windows workstation (GE Yokogawa Medical Systems, Ltd.), and measurements were made using slices where all apatite areas were depicted. For each apatite area, the maximum diameter of the region of interest (ROI) was established on the same slice on a screen, and the Hounsfield unit (HU) value was measured. The measurements were made three times and the average value was used.

First, a regression line was plotted using the HU value of each apatite area of the experimental phantom and the apatite values of the relevant areas of the reference phantom, and the correlation coefficient was found. Then the reference BMD of the reference phantom was assumed to be the HU value of an area, and the accuracy of the obtained BMDs was examined.

Under the following conditions, we examined how the measured values were affected by (A) the movement of the reference phantom’s center of the scan when scanning the experimental phantom and (B) the rotation and tilting of the experimental phantom (Fig. 4):

1. Upward and downward movements of the reference phantom’s center of the scan at 1-cm increments with a maximum of 5 cm,
2. Left and right movements of the reference phantom’s center of the scan at 1-cm increments with a maximum of 5 cm,
3. Left and right rotations of the experimental phantom at 15° increments with a maximum of 45°, and
4. Tilting of the experimental phantom relative to the long axis at 15° increments with a maximum of 30°.

Statistical analysis
The Tukey-Kramer method was used to test for differences between the known value and the measured values for each set of conditions, and the significance level was set at the 95% confidence interval.

III. Results

1. The $R^2$ was 0.9997 for the regression line plotted using the HU value from each apatite area of the experimental phantom and the relevant apatite values of the reference phantom, indicating a strong correlation (Fig. 5).
2. When BMDs were calculated from the HU values of the reference phantom using the regression line, the BMDs were 76.2 mg/ml at the 75-mg/ml site and 127.6 mg/ml at the 125-mg/ml site, indicating close values ($p>0.05$) (Fig. 6).

(Fig. 5) Accuracy of the experimental jawbone phantom using the reference jawbone phantom’s center of the scan
Relationship between HU values and apatite values (mg/ml). A positive correlation was observed ($R^2=0.999$).

(Fig. 6) Values of the known BMD materials calculated from the experimental jawbone phantom using the reference jawbone phantom’s center of the scan
(Fig. 7) Results observed when the reference jawbone phantom’s center of the scan was moved upward and downward
(Fig. 8) Results observed when the reference jawbone phantom’s center of the scan was moved to the right and left
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(3) When the reference phantom’s center of the scan was moved upward and downward, the measured value tended to increase with increasing downward movement and to decrease with increasing upward movement. When the center was moved upward and downward 5 cm maximally, the measured value was 78.2±0.3 mg/ml and 72.9±1.1 mg/ml, respectively, at the 75-mg/ml site (Fig. 7). There was no significant difference between 75 mg/ml and these values (p>0.05).

(4) When the reference phantom’s center of the scan was moved to the right and left, the measured value tended to increase as the center increasingly moved away from the previously described standard center. When the center was moved maximally 5 cm to the right and left, the values were 81.6±2.2 mg/ml and 81.2±14.6 mg/ml, respectively, at the 75-mg/ml site. There was no significant difference between 75 mg/ml and these values (p>0.05) (Fig. 8).

(5) When the experimental phantom was rotated to the right or left, the measured value tended to increase with increasing rotation angle. When the experimental phantom was rotated maximally 45° toward the right and left, both values were 76.2±1.1mg/ml at the 75-mg/ml site (Fig. 9), indicating no significant difference between these numbers (p>0.05).

(6) When the experimental phantom was tilted relative to the long axis at 15° increments, the measured value was 77.9±16.1 mg/ml at 15° and 78.9±16.4 mg/ml at 30°, indicating significantly high values relative to that at 0° (p<0.05) (Fig. 10).

IV. Discussion

Bone quality is often classified clinically by the HU value, the bone quality classification of Lekholm and Zarb, and the bone quality and BMD classification of Misch. The Lekholm and Zarb classification categorizes bone quality into four types based on the proportion of cortical bone and trabecular bone. Type I is composed of overall hard bone quality; type II a thick cortical layer and dense trabecular bone; type III a thin cortical layer and trabecular bone of good quality and strength; and type IV a soft bone quality with a thin cortical layer and low-density trabecular bone. In general, bone quality suitable for implant treatment is considered to be of type II and type III. Type I and IV bones are thought to be unfavorable for implant treatment. Type I bone can become overheated during the preparation of the implant socket and type IV bone will result in poor fixation at the initial stage. This classification method is simple and easy and enables representation of bone quality to a certain degree. However, a quantitative method is necessary for diagnostic examination of bone quality, which is limited to the implant placement site, and for diagnostic examination of long-term changes.

The Misch classification categorizes bone quality into four groups based on BMD and five groups using HU values. D1 (HU values>1250) is primarily cortical bone and has a high bone strength of 9-10 on a scale of 1 to 10. D2 (HU values=850-1250) is cortical bone and coarse trabecular bone, which form a thick layer at the alveolar crest, and has a bone strength of 7-8. D3 (HU values=350-850) has a thin cortical layer in the alveolar crest region and fine trabecular bone and has a bone strength of approximately 3-4 (approximately 50% of D2). D4 (HU values<350) has a small cortical layer, is primarily fine trabecular bone, and has a bone strength of approximately 1-2. D5 (HU values<150) is primarily fine trabecular bone and has a bone strength of approximately 1. These types of bone are classified not only visually but also by CT value. Thus, they clearly represent the relationship between bone density and appearance. However, there are still many unknowns regarding how the actual BMD is affected by the positional changes of the jawbone during CT scanning. Our study aimed to elucidate this relationship using an experimental jawbone phantom that we prepared.

The experimental jawbone phantom was created in an arch form because it will be placed on a patient’s jawbone in clinical practice. This phantom contained apatite rods with BMDs of 0, 50, 100, 150, and 200 mg/ml. A regression line was plotted using these apatite values and the measured HU value in each area after scanning. The $R^2$ was 0.9997, indicating a strong correlation between these values. Kido et
al.\textsuperscript{9} collected 58 jawbone samples from 6 individuals and evaluated the relationship between bone compressive strength and BMDs (HU values calculated from apatite values) measured using QCT. They reported a strong correlation between them. Another report has also shown a correlation between bone compressive strength and BMDs calculated from HU values.\textsuperscript{10} Our present study examined the apatite values found from the HU values, which were obtained for the known apatite amounts of 75 mg/ml and 125 mg/ml. These apatite values were found to be similar to the known amounts: 76.2 mg/ml at the 75-mg/ml site and 127.6 mg/ml at the 125-mg/ml site. These results suggested that an accurate apatite amount can be obtained when the apatite amount at a jawbone site is obtained using the HU values measured from the experimental jawbone phantom.

When the reference phantom's center of the scan was moved upward and downward, the measured value tended to increase with increasing downward movement and to decrease with increasing upward movement. When the reference phantom's center of the scan was moved to the right and left, the measured value tended to increase as the center increasingly moved away from the previously described standard center. When the experimental phantom was rotated to the right and left, the measured value tended to increase with the increasing rotation angle. However, there was no significant difference between the known apatite value and the measured values in any of the above described conditions. These findings suggested that even if the experimental phantom is rotated 45° relative to the reference phantom and the center of the scan is moved approximately 5 cm maximally from the reference phantom, an accurate apatite value can be calculated if the apatite amount at a jawbone site is obtained from the HU value. As aforementioned, there was no significant difference in measured values when the reference phantom's center was moved 5 cm maximally upward or downward and to the right or left. These findings suggested that there is no major effect on bone quality diagnosis even if a subject is not in the correct position, as described above, during CT scanning.

When the experimental phantom was tilted relative to the long axis anteriorly and posteriorly at 15° and 30°, the measured values were significantly higher than at 0°. These results suggest that if the experimental phantom is tilted from the reference phantom and relative to the long axis, the apatite amount at a jawbone site, which is obtained from the HU value, might not be accurately represented. These results also suggested that when this experimental jawbone phantom is used on a patient, it must be positioned so that its long axis will be perpendicular to the CT-slice plane. When the phantom was tilted, the measurement error was 10-20 HU. This range of measurement error is not large enough to change the BMD classification of Misch. This finding suggested that the diagnosis of BMD is not affected by the error in BMD, which is caused by the positional shift of the subject during CT scanning.

If this experimental jawbone phantom is used with correct positioning, one might be able to measure an accurate apatite amount from the HU value at a jawbone site. The establishment of such a quantitative examination method enables preoperative BMD diagnosis. This method is thought to be effective to assess the treatment predictability from the perspective of osseointegration achievement and maintenance and the intraoperative risk of implant treatment. In addition, this method enables diagnostic examination of bone quality, which is limited to the implant placement site, and diagnostic examination of long-term changes. The method is also thought to be useful in the evaluation of periimplant bone conditions of patients with periimplantitis and of patients who had to take drugs for osteoporosis after implant placement.

In the future, we plan to conduct a clinical study using this experimental jawbone phantom and to establish a method to measure quantitatively bone apatite amounts in the oral region. We think that such efforts will enable the diagnosis of bone quality before implant treatment and enable the evaluation of periimplant bone health after surgery.

V. Conclusion

The results of our study suggested that the experimental jawbone phantom is effective in accurately measuring the BMD at any site of the patient jawbones. Although the measured BMD might change with the patient position during CT scanning, there should be no change in the BMD that is large enough to greatly affect the bone quality diagnosis. However, it is necessary to place the long axis of the phantom perpendicular to the CT-slice plane when placing it near the patient's jawbone.

References
