The usefulness of cone-beam computed tomography gray values for alveolar bone linear measurements

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ABSTRACT

Objectives: To test a proof-of-concept that the accuracy and reliability of alveolar bone height measurements from orthodontic grade (large field-of-view [FOV], large voxel-size) cone-beam computed tomography (CBCT) images may be improved by using pixel gray values.

Materials and Methods: Twenty fresh cadaver pig heads underwent CBCT scans (17×23 cm FOV, 0.4-mm voxel size). Buccal alveolar bone heights of maxillary first molars were measured using the conventional vision-based (VB) and the proposed gray value–assisted (GVA) methods. The GVA methods entailed localization of landmarks through observation of gray value pattern changes across tissue boundaries followed by mathematical calculation of distances between landmark pixels. Interrater reliability and accuracy of CBCT measurements made by all methods were statistically analyzed by comparing with physical measurements (gold standards).

Results: The interrater reliability of CBCT measurements made by GVA methods was comparable to physical measurements but higher than those made by the VB method. The GVA (bend-down pattern) method yielded average measurements similar to physical measurements, while those obtained by the VB and the GVA (straight pattern) methods were significantly larger (repeated measures analysis of variance, $P < .001$). The GVA (bend-down pattern) method also produced significantly more measurements within one voxel size of physical measurements than did the VB and GVA (straight pattern) methods (Chi-square tests, $P < .017$).

Conclusions: These data confirm a concept that local gray value change patterns may be used to improve the accuracy and reliability of alveolar bone height measurement from large FOV and large voxel-size CBCT images. (*Angle Orthod.* 2018;88:227–232.)

KEY WORDS: CBCT; Alveolar bone; Linear measurement; Gray values

INTRODUCTION

Cone-beam computed tomography (CBCT) images are being used in orthodontics to assess alveolar bone changes associated with treatments such as rapid palatal expansion[1,2] and incisor proclination.[3,4] For orthodontic needs, these images are often scanned under large field-of-view (FOV) and large voxel-size (0.3–0.4-mm) settings. Unfortunately, compared to small-FOV small voxel-size CBCT scans, these orthodontic-grade CBCT images tend to result in fairly unreliable and inaccurate alveolar bone height measurements.[5–8]

This problem is attributable to factors affecting CBCT image quality, including scanning parameters,[8] soft tissue conditions,[5] artifacts/noise,[9] target structure type/size/location,[6,7] and factors affecting the analysis process, such as measurement methods and rater's experience. To date, the predominant method to measure CBCT linear distance has been vision based (VB), which requires visual determination of structure

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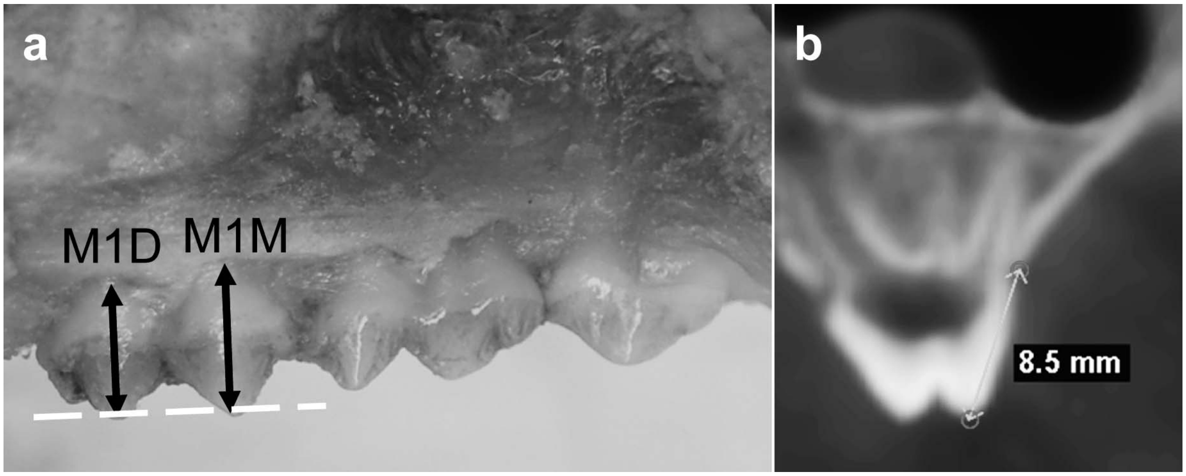

Figure 1. (a) Physical measurements of alveolar bone height were measured between the mesial (M1M) and distal (M1D) cusp tips and alveolar crests, perpendicular to the molar occlusal table (broken line), using a digital caliper. (b) Vision-based (VB) measurements of alveolar bone height were measured between visualized cusp tips and alveolar crest landmarks in the coronal plane using a digital line tool.

boundaries before applying digital measurement tools. This method has been used on alveolar bone,[5] temporomandibular joint,[10] airway space,[11] etc.

To visually measure alveolar bone height, enamel and alveolar crest landmarks need to be identified. Much ambiguity is involved in identifying the alveolar crest as a result of its proximity to the cementum, which has similar brightness/darkness to bone. When large FOV, large voxel-size (0.4-mm) CBCT images were used, the interline distance required to visually separate four lines has been found to be 0.86 mm,[12] significantly larger than the scan voxel size and average periodontal ligament (PDL) thickness (0.5 mm). Human vision is also influenced by lighting, fatigue, grayscale ability, and visual acuity. CBCT images typically contain between 12/16 bits per pixel, which corresponds to 4096 to 65,536 shades of gray, while even optimal human vision can only discriminate 700–900 simultaneous shades of gray.[13] These factors can substantially increase interrater variability of alveolar bone height measurements from CBCT images.[5–8]

To overcome these vision-associated limitations, it is proposed that the pixel gray values may be extracted from CBCT images to assist in alveolar bone height measurement. More specifically, by integrating gray value information with anatomical characteristics of alveolar bone, localization of the alveolar crest landmark may be more accurate and reliable than with the VB method. This study was undertaken to test this proof-of-concept.

MATERIALS AND METHODS

Specimens

Twenty fresh cadaver heads of domestic pigs (*Sus scrofa*), aged 5 months and equivalent to early adolescent humans in craniofacial skeletal maturity and alveolar bone morphology,[14,15] were collected from the Ohio State University animal facility.

CBCT Scans

With all facial and intraoral soft tissues kept intact, the pig heads underwent CBCT scans using an iCAT 17-19 Platinum CBCT machine (Imaging Sciences International, Hatfield, Pa). The scan settings were 120 kVp, 5 mA, 0.4-mm voxel size, 17 $\times$ 23-cm FOV, and 8.9-second scanning time, which were typical settings used for some orthodontic patients.[1,2]

Specimen Dissection and Physical Measurements of Alveolar Bone Height

After CBCT scans, the pig heads were dissected to expose the buccal alveolar bones of the maxillary molars. Clinically, CBCT scans have been commonly used to assess alveolar bone changes in this region after orthodontic treatment.[1,2] All soft tissues covering the alveolar bone was carefully removed to avoid bone damage. Then, physical measurements of bone height were made at the mesial and distal cusps of the first permanent molar (M1) (Figure 1a). The linear distance between the cusp tips and the alveolar crest, in a line perpendicular to the occlusal plane (determined by the cusp tips), was measured by two calibrated and independent raters (SP, KE) using a digital caliper (precision, 0.001 mm). All locations were measured twice and averaged.

Measuring Alveolar Bone Height from CBCT Images Using a VB Method

All CBCT DICOM files were analyzed by three calibrated and independent raters (SP, KE, BCT)

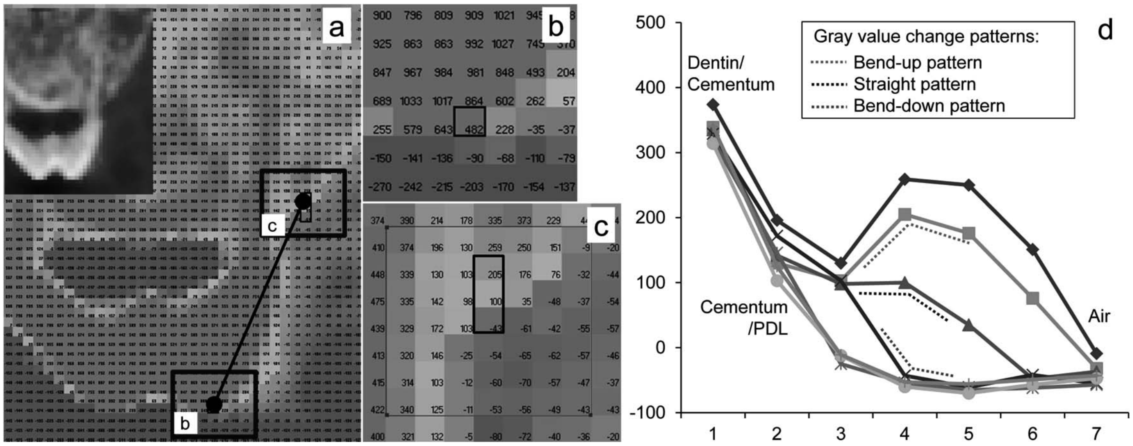

Figure 2. Gray value–assisted (GVA) method for measuring alveolar bone height: (a) Extraction of gray values from a cone-beam computed tomography (CBCT) coronal image and depicting the rough contour of tooth and alveolar bone; (b) Determination of cusp tip landmark as the most occlusal high-value pixel near the cusp center; and (c, d) Determination of alveolar crest landmark based on line graphs showing bend-down or straight patterns.

blinded to image identities. The images were uploaded to Dolphin-3D (Dolphin Imaging and Management Solutions, Chatsworth, Calif), reoriented first in the frontal and sagittal views to parallel the occlusal plane with the floor, then in the axial view, bisect the head with the midsagittal plane. Subsequently, the first maxillary molar buccal alveolar bone height was measured in the coronal view using a digital caliper (Figure 1b), in similar orientation to physical measurements on specimens. During analyses, the raters were allowed to zoom in/out and change the brightness/contrast of the images as needed. For each section, duplicate measurements were obtained and averaged.

Measuring Alveolar Bone Height from CBCT Using GVA Methods

The same raters (SP, KE, BCT) conducted these analyses. First, the DICOM files were imported into ImageJ software (National Institutes of Health, Baltimore, Md) and converted into TIFF format. Then, the stacked three-dimensional TIFF file was reoriented using the TransformJ plugin[16] following the same protocol used for the VB method. After reorientation, three consecutive images in the coronal plane passing through the cusp tip for each molar location were collected for analysis by the three raters, as follows.

First, the gray values of each image were extracted from ImageJ and exported to an Excel worksheet (Microsoft Office 2010) (Figure 2a), in which the 20th, 50th, and 85th percentile groups of the gray values were outlined and labeled with three different colors to depict the approximate contour of the tooth and adjacent alveolar bones (Figure 2b). Next, the raters determined the enamel and alveolar crest landmarks to particular pixels. For the former, it was proposed that it was characterized by a large gray value reduction when transitioning from enamel to air. In the Excel sheet, the most occlusal pixel with a large positive gray value was then determined as the enamel landmark (Figure 2c). For the alveolar bone crest landmark, it was proposed that it was located at the junctional area of dentin/cementum, periodontal ligament, alveolar bone, and gingiva. To locate this pixel, the raters identified a 7 $\times$ 7-pixel area in the cementoenamel junction (CEJ)–alveolar process region containing the alveolar crest and its surrounding tissues (Figure 2c), followed by plotting the gray values of all pixels in that area into a line graph (Figure 2d). By assessing the gray value change in each line from the high-value end (representing dentin/cementum) to the low-value end (representing the buccal gingiva/air), the lines were categorized into three patterns. The "bend-up" pattern was present in lines away from the cervical region and was characterized by an upward change before reaching the buccal gingiva/air end. The "straight" pattern was characterized by a relatively straight slope descending from the high-value end to the low-value end. The "bend-down" pattern was characterized by a flat or small downward change of gray values before reaching the buccal gingiva/air end. It was proposed that while the "bend-up" pattern indicates the presence of relatively thick alveolar bone, the thin and tapered alveolar crest is very likely located in the "straight" or "bend-down" patterns. Thus, the pixel in the only one "straight" (GVA-ST) line and the first "bend-down" pattern line (GVA-BD) patterns immediately before reaching the buccal gingiva/air side were selected as the possible alveolar crest landmark (Figure 2c,d).

Subsequently, the linear distance between the enamel and alveolar crest landmark was calculated using the Pythagoras principle ($a^2 + b^2 = c^2$). The

Table 1. Interrater Reliability (Intraclass Correlation Coefficient [ICC]) of Alveolar Bone Height Measurements

	Measurement Methods[a]			
	PHY	VB	GVA-ST	GVA-BD
Left mesial cusp	0.870	0.844	0.950	0.950
Left distal cusp	0.928	0.941	0.914	0.913
Right mesial cusp	0.925	0.675	0.903	0.904
Right distal cusp	0.946	0.851	0.960	0.960
All sides/locations combined	0.934	0.814	0.945	0.945

[a] PHY indicates physical method; VB, vision-based method; GVA-ST, gray value–assisted straight pattern method; and GVA-BD, gray value–assisted bend-down pattern method.

values of "a" and "b" were obtained by multiplying pixel numbers in the horizontal and vertical dimensions, respectively, by 0.4 mm (pixel size).

Statistical Analysis

Interrater reliability was assessed by intraclass correlation (ICC) tests. The accuracy of CBCT measurements was assessed in two ways. First, the measurements (averaged among raters) were compared among methods (PHY, VB, GVA-ST, and GVA-BD) by a mixed-model repeated-measures analysis of variance (ANOVA) test with Bonferroni post hoc comparisons. Second, the absolute difference between each CBCT measurement of each rater and its corresponding physical measurement was calculated. The proportions of measurements within 1 voxel (0.4 mm) of difference were compared among the VB, GVA-ST, and GVA-BD methods by Chi-square tests with Bonferroni adjustment of the alpha level to .017.

RESULTS

One site was excluded from analysis as a result of bone damage, so the results were based on measurements from 79 sites.

Reliability of Alveolar Bone Height Measurements

As shown in Table 1, for each method, there were negligible differences in ICC coefficients between the mesial and distal cusp locations. Overall, the VB method had the lowest reliability, while the PHY and GVA-BD methods had the highest reliability.

Accuracy of Alveolar Bone Height Measurements

The ANOVA test (Figure 3a) showed no significant interactions between the methods and jaw side/cusp locations, but it showed a highly significant difference among methods ($P < .0001$). Post hoc comparison found that the average GVA-BD and physical measurements were similar, but both were significantly lower than those from the VB and GVA-ST methods.

The Chi-square tests showed that the GVA-BD method yielded a significantly larger proportion (54%) of measurements to be within 0.4 mm of physical measurements than did the VB (42%) and the GVA-ST methods (29%) (Figure 3b).

DISCUSSION

This study tested a proof-of-concept that gray values may be used to improve the reliability and accuracy of alveolar bone height measurements from large voxel-size, large FOV CBCT images used in orthodontics. The data demonstrated that by identifying a specific "bend-down" pattern of gray value change in the region where dentin/cementum transitions to buccal gingiva/air, the alveolar crest landmark can be more reliably and accurately localized than with the currently used VB method.

For reliability assessment, three and two raters were used for CBCT and physical measurements, respectively. It has been found that an optimal combination of the number of raters and number of test samples depends on the relative ratio (between-rater variance/error variance), and when the ratio is higher, a larger number of raters may increase the precision to estimate interrater reliability through ICC tests.[17] CBCT measurements involve multiple steps and likely have a higher between-rater variance than do physical measurements, which are relatively straightforward. Therefore, we used three instead of two raters for CBCT measurements to improve the precision of the reliability assessment.

The GVA method produced higher interrater reliability measurements than did the VB method, and interrater reliability of the VB method in the current study was comparable to those values reported previously,[8] suggesting that an improvement was made with the GVA method. Very likely this was because it minimized the influence of rater-related variations in visual acuity, experience, and carefulness in visually measuring CBCT images. More specifically, the GVA method relies on observation of gray value pattern change shown in linear graphs, which depict the gingival-alveolar bone–PDL interface region (Figure 3). Visual judgement is only required for identifying a relatively large region containing the enamel or the alveolar crest by evaluating the tooth contour based on gray value mapping, a process not requiring precision to particular pixels; thus, rater's variations in visual acuity have a negligible impact. Subsequent localization of the landmarks to particular pixels is completely accomplished through evaluating pattern changes of gray values, a process that is independent of raters'

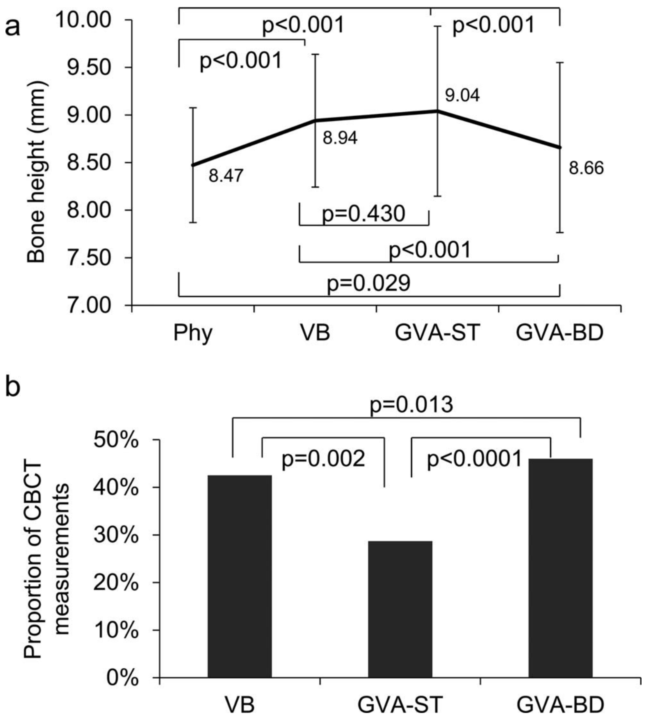

Figure 3. Accuracy of cone-beam computed tomography (CBCT) measurements: (a) Gray value–assisted (GVA) bend-down pattern methods produced similar average measurements to physical measurements, while vision-based (VB) and GVA straight pattern methods produced significantly larger average values. (b) The GVA bend-down pattern method produced significantly more measurements within 1 voxel size (0.4 mm) of physical measurements than did the VB and GVA straight pattern methods.

visual acuity. Finally, distance measurement is accomplished through mathematical calculation, making the raters' variation in placing the digital measurement tools in the VB method a nonfactor.

As for accuracy, the GVA-BD method yielded a significantly smaller average deviation (0.19 mm) from physical measurements than did the VB method (0.47 mm) (Figure 3a), and a significantly higher proportion of measurements from the GVA-BD method were within 1 pixel size from physical measurements than with the VB method (Figure 3b). An increase in the distances between cusp tip and alveolar crest landmarks relative to physical measurements indicates an underestimation of alveolar crest level, which has been reported in other studies[7,18] when alveolar bone height was measured from CBCT images using the VB method. This is largely because the crest is too thin to be visualized. As found by Sun et al.,[6] when the crest thickness was intentionally reduced to near 1 voxel size, it becomes invisible to human eyes on the CBCT images.

By comparing between the GVA-ST and GVA-BD patterns, the current data can further explain why thin alveolar crests become invisible on CBCT images.

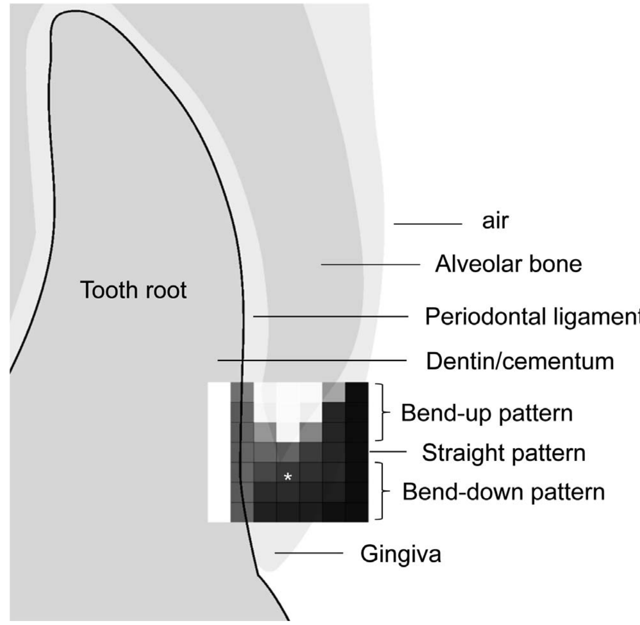

Figure 4. Schematic illustration of typical gray value changes around the alveolar crest. Each square represents 1 pixel, with its relative gray value indicated by the displayed brightness/darkness. The alveolar crest landmark (*) is more likely located in a pixel showing air-like darkness due to partial volume effect, which is consistent with the bend-down pattern.

Based on gray value changes around the alveolar crest and gingiva, it was initially speculated that the alveolar crest landmark is most likely localized on the "straight" pattern line, namely, the transition from bone-level gray values to gingiva-level gray values. This speculation was rejected, as the first line showing the "bend-down" pattern (GVA-BD) had a much closer match with the physical measurements than did the "straight" pattern (GVA-ST) (Figure 3b). Essentially, the alveolar crest landmark pixel identified by the "bend-down" pattern line had the same low gray value as the gingiva.

The reason that the alveolar crest showed a gingiva-level gray value is likely due to the partial volume effect, which produces the gray value of a voxel by averaging all structures contained in that voxel. As schematically illustrated in Figure 4, anatomically, most alveolar crests are only 1–2 voxel size thick, which may be divided into several pixels during image reconstruction. Thus, the voxel that contains the crest also contains a large proportion of gingival tissue,causing the average gray value to be more similar to the latter and making it impossible to distinguish with bare eyes. The GVA-BD method overcomes this limitation by mathematically analyzing pattern changes of gray values of multiple surrounding voxels (Figure 4).

As with many proof-of-concept studies, this study has several potential limitations. First, despite efforts to match the planes and landmarks used between the gold standard (physical) and CBCT methods, there may still be minor discrepancies between physical specimens and CBCT images. Second, the raters used the same reoriented scans for CBCT analysis, which may potentially affect the reliability assessment. However, since the reorientation process was standardized, such an impact should be small. Additionally, the current study has a limited scope, and the GVA-BD method only allows landmark identification and measurement within the same two-dimensional plane. Future efforts may expand it to three-dimensional planes. Finally, the current GVA-BD method involves the use of two software programs (ImageJ and Excel) and a relatively tedious process. For greater clinical applicability, future efforts are needed to simplify or automate the process into one software module.

CONCLUSIONS

- This study confirmed a proof-of-concept that alveolar bone height measurements from large voxel-size, large FOV CBCT images can be improved by identifying a “bend-down” gray value pattern change in the CEJ–alveolar bone region.
- This new method may substantially minimize the variation and inaccuracy involved in human vision-based methods.

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