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Accuracy of cone-beam computed tomography at different resolutions assessed on the bony covering of the mandibular anterior teeth

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Introduction: The aim of this study was to determine the accuracy of cone-beam computed tomography (CBCT) with different voxel resolutions. Measurements were made of the bony covering of the mandibular anterior teeth because this region is crucial in orthodontic treatment planning. **Methods:** CBCT data at 2 resolutions (0.125-mm and 0.4-mm voxels) were collected from 8 intact cadaver heads. The vertical position of the mucogingival junction was clinically assessed. After removal of the gingiva, vertical and horizontal bony measurements were taken, and the buccal alveolar bone margin was determined. Anatomic bony measures were compared with the CBCT measures, and the correlation of the mucogingival junction measures to the buccal alveolar bone margin measures was evaluated. **Results:** Bony measures obtained with CBCT were accurate and differed only slightly from the physical findings. The mean differences, ranging from −0.13 to +0.13 mm, were statistically not significant, but the limits of agreement showed discrepancies in the measurements as large as 2.10 mm, depending on measurement and resolution. Buccal alveolar bone margin measurements correlated with the mucogingival junction measurements ($P < 0.001$). On average, the mucogingival junction was 1.67 mm more apical than the buccal alveolar bone margin (CI 95%, 1.35-1.98 mm). **Conclusions:** CBCT renders anatomic measures reliably and is an appropriate tool for linear measurements. Presence of soft tissue as well as different voxel size affect the precision of the data. A customized resolution protocol must be chosen according to the accuracy needed. However, even the 0.125-mm voxel protocol does not depict the thin buccal alveolar bone covering reliably, and there is a risk of overestimating fenestrations and dehiscences. The mucogingival junction appears to follow the buccal alveolar bone margin in a parallel line. (Am J Orthod Dentofacial Orthop 2012;141:41-50)

Cone-beam computed tomography (CBCT) has been used in the craniofacial region since 1998,[1] and scientific contributions in orthodontics have been published since 2003.[2] This new technology is attractive because of its high performance, low cost, and reduced radiation dose compared with conventional computed tomography. These advantages have led to a clearer definition of clinical applications of CBCT in implantology, oral and maxillofacial surgery, and orthodontics. However, as with every new development, CBCT data should be validated for their accuracy. Although the need to ascertain CBCT accuracy is not controversial, its accuracy has not been satisfactorily verified.

The first studies of CBCT accuracy in the oral and maxillofacial region appeared in 2004,[3,4] and since then various attempts have been made to analyze the accuracy of these data based on the comparative measurements of physical objects.[5-22] Every study made to ascertain the accuracy encounters the problem of what model to use to depict the anatomic truth reliably. Physical models, dry skulls, and mandibles immersed in solutions are common approaches to overcome this problem. These methodologies, however, do not accurately reflect clinical applications. The lack of soft tissues has been acknowledged to be a serious limitation in these studies,[13,23] particularly since absence of soft tissues would likely facilitate the detection of bone surfaces.[15] Use of cadaver heads would partly overcome this methodologic shortcoming.[13]

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An additional factor that could influence accuracy is the resolution of the obtained data volume. CBCT image data are acquired in digital format from a single 360° rotational scan. Image reconstruction from these projections is made by using an algorithm for volumetric tomography that renders the information into 3-dimensional images consisting of voxel elements.[24] The size of each voxel is determined by its height, width, and thickness. Therefore, a study evaluating the accuracy should preferably also contain a comparison of different voxel settings, since the results depend not only on the examined object, but also on the inherent qualities of the acquired data. This way, the influence of both aspects can be juxtaposed.

The mandibular anterior incisors play an essential role in orthodontic treatment planning because of their restricted anatomic leeway in the symphysis. Hence, the assessment of the bony covering is pivotal when planning any tooth movement of the mandibular incisors, since it has been demonstrated that excessive sagittal movements or tipping can result in significant recession of the gingival margin and in bony dehiscences.[25-31] Although some investigators found no association between orthodontic tooth movement and gingival recessions,[32-35] it is commonly agreed that an especially narrow symphysis is an etiologic factor in the development of fenestrations and dehiscences.[35,36] It is therefore important to investigate the possible limitations of CBCT data beyond the actual voxel sizes and to evaluate the clinical relevance of the obtained information about the bony covering.

The aims of this study were threefold: (1) to validate the accuracy of linear measurements of CBCT on intact cadaver heads, (2) to compare different voxel size settings and their impacts on the achieved accuracy, and (3) to examine the clinical relevance of the acquired data.

To validate the accuracy of the radiologic measures, the following statistical hypothesis was tested: there is no difference between the clinical and radiologic measurements.

MATERIAL AND METHODS

Eight intact human cadaver heads (5 women, 3 men; age range, 65-95 years) with complete canine-to-canine dentitions in the mandibular front were supplied by the Anatomical Institute of the University of Zurich in accordance with state and federal regulations (voluntary body donation program on the basis of informed consent), the Convention on Human Rights and Medicine,[37] and the recommendation of the Swiss Academy of Medical Science.[38] Perfusion was carried out within 4 days after death with a fixation liquid consisting of the following formula: 2 parts alcohol (70%), 1 part glycerine, and 2% almudor (containing 8.10% formaldehyde, 10% glyoxal, and 3.70% glutaraldehyde). No specimen had an inflammation or recessions in the mandibular front.

Two CBCT scans (KaVo 3D eXam, KaVo Dental AG, Brugg, Switzerland) with different settings were performed on each head: high resolution (0.125-mm voxel) and low resolution (0.4-mm voxel) at 120 kV and 5mA. The radiologic measurements were made with a postprocessing software tool for DICOM data (eXam Vision software, Imaging Sciences International, Hatfield, Pa). All images were reconstructed by using multiplanar reformatting perpendicular to the curvature of the dentition, thereby enabling the depiction of every tooth in its buccolingual profile (Fig 1, *A* and *B*).

The radiologic measures were analogous to the clinical examination of the vertical (incisal edge-buccal alveolar bone margin) and horizontal bony measures, as shown in Figure 1, *C*. All measurements were taken twice by the same observer (R.P.), at least a week apart.

The clinical examination consisted of 3 measurements (Fig 1, *C*).

1. Soft-tissue measurement (incisal edge-mucogingival junction; IE-MGJ): the width of the attached gingiva was determined for all mandibular front teeth. The most basal point of the undulated mucogingival junction was used to evaluate the distance to the incisal edge (canine to canine, n = 48). The attached gingiva was stained with Schiller solution as described by Fasske and Morgenroth[39] (iodide pure: potassium-iodide: distilled water = 10:20:300) to facilitate locating the junction.
2. Vertical bony measurement (incisal edge-buccal alveolar bone margin; IE-ABM): after the gingiva was removed, the distance from the buccal alveolar bone margin to the incisal edge was determined for every tooth (canine to canine, n = 48). Since the bone margin is not a horizontal line but lunar shaped, the most apical point was chosen.
3. Horizontal bony measurement (H): a thin slat of the alveolar bone was removed with a scalpel. The thickness of the alveolar bone covering was measured at a distance of 15 mm (n = 48) from the incisal edge (incisal edge-horizontal). Occasionally, a second site was chosen at 18 mm (n = 13) from the incisal edge to increase the total measurements taken (n = 61).

Two electronic digital calipers were used for the clinical measures (accuracy of 0.01 mm): a customary caliper for measuring the length and the other especially designed for depth measurement. All clinical measures were repeated on different occasions and the mean value was used.

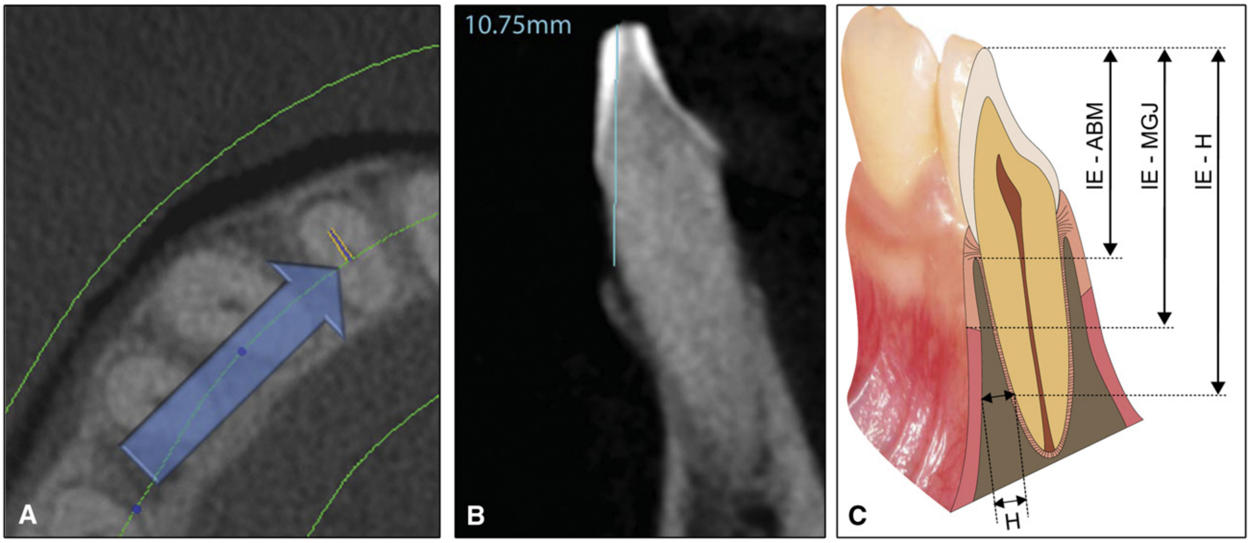

Fig 1. A, Axial rendering of the data showing the perpendicular curve of the reformatted slices along the *thin green middle line* (*blue arrow* points to the slice depicted in *B*; *bold green lines*, outer boundaries of the curve; *orange lines*, thickness of slice depicted in *B*. **B**, Representative reformatted image from which the radiologic measurements were taken (*light blue line*, incisal edge-buccal alveolar bone margin; IE-ABM). **C**, Graphic illustration of measurements taken: *IE*, Incisal edge; *ABM*, alveolar bone margin; *MGJ*, mucogingival junction; *H*, horizontal measurement. The measurements *IE-ABM* and *H* were taken clinically and radiologically, and the *IE-MGJ* measurement was taken only clinically.

Table I. Intraclass correlation coefficients (ICC) for all 4 protocols for intraobserver repeatability

ICC	*Low resolution*	*High resolution*
Vertical measurements	0.96	0.99
Horizontal measurements	0.90	0.95

Statistical analysis

Two standard statistical software packages (version 17; SPSS, Chicago, Ill; and version 11.4.1.0; MedCalc, Mariakerke, Belgium) were used for data analysis. To determine intraobserver reliability, the intraclass correlation coefficient for absolute agreement based on a 1-way random-effects analysis of variance (ANOVA) was calculated for the repeated radiologic measurements from the same observer for all 4 protocols (low and high resolutions, vertical and horizontal measures).

Descriptive statistics for the clinical measurements and for the differences between the radiologic and clinical measures for each category were computed separately. In addition, the 95% CI was calculated, and the absolute measurement error (AME) was determined according to the following equation:

$$\text{AME} = |\text{radiological measurement - clinical measurement}|$$

To disclose deterministic differences between both methods of measurement, a 1-sample Student *t* test was applied to the differences. Moreover, the Bland-Altman method[40–43] was applied, and the limits of agreement were identified. The Levene test was used to detect an increase of variability of the differences with the increase of the magnitude of the measurements. The Pearson correlation coefficient was computed to evaluate the association of soft-tissue measures to bony measures. In addition, the regression plot between soft-tissue measures to bony measures together with the 95% prediction interval was provided. The assumption of normality for the differences of soft to bony tissues was investigated by the Kolmogorov-Smirnov test. The results of the statistical analysis with *P* values smaller than 5% were considered to be statistically significant.

RESULTS

The intraclass correlation coefficient showed good repeatability of the radiologic measures. The values for all 4 protocols ranged between 0.90 and 0.99 as illustrated in Table I. The results of the descriptive statistics for the clinical measurements are provided in Table II.

The accuracy of the scans proved to be acceptable for both the high-resolution and low-resolution protocols. The absolute measurement errors for all 4 protocols are given in Table III. The descriptive statistics for the differences of the measurements and the 1-sample Student *t* test are shown in Table IV. The mean difference between

Table II. Descriptive statistics of clinical measurements

Clinical measurements	*Mean (mm)*	*Median (mm)*	*SD (mm)*	*95% CI (mm)*
Vertical (n = 48)	12.13	11.93	1.58	(11.67-12.58)
Horizontal (n = 61)	1.02	0.82	0.77	(0.82-1.22)
Distance ABM-MGJ (n = 48)	1.67	1.78	1.08	(1.36-1.98)

ABM-MGJ, Alveolar bone margin to mucogingival junction.

Table III. Absolute measurement error for all 4 protocols

Absolute errors	*Mean (mm)*	*Median (mm)*	*SD (mm)*	*99% CI (mm)*
Vertical, low resolution (n = 48)	0.70	0.53	0.84	(0.37-1.02)
Vertical, high resolution (n = 48)	0.34	0.21	0.50	(0.14-0.54)
Horizontal, low resolution (n = 61)	0.54	0.42	0.46	(0.38-0.69)
Horizontal, high resolution (n = 61)	0.37	0.25	0.43	(0.22-0.52)

Table IV. Descriptive statistics, 1-sample *t* test, and 95% CI values for differences and limits of agreement (positive numbers represent overestimations, and negative numbers represent underestimations of measurements with CBCT with respect to clinical measurements [Clin])

Differences CBCT-Clin	P *value*	*Mean difference (mm)*	*SD (mm)*	*Range (mm)*	*95% CI (mm)*	*Limits of agreement (mm)*
Vertical, low resolution (n = 48)	0.79	0.04	1.09	8.48	(−0.27-0.35)	(−2.1-2.2)
Vertical, high resolution (n = 48)	0.15	−0.13	0.59	3.91	(−0.30-0.05)	(−1.3-1.0)
Horizontal, low resolution (n = 61)	0.63	0.04	0.71	4.18	(−0.14-0.23)	(−1.4-1.4)
Horizontal, high resolution (n = 61)	0.08	0.13	0.55	3.62	(−0.02-0.28)	(−1.0-1.2)

the clinical and radiologic measures were for all protocols close to 0 and ranged between −0.13 and +0.13 mm; 0 was within the 95% CI bounds, confirming no systematic bias in all 4 radiologic readings. The 1-sample *t* test showed no significant differences between the physical and the radiologic measures; consequently, the statistical hypothesis could not be rejected.

To validate the different measurements, the differences between the radiologic and clinical measurements were plotted against the average as recommended by Bland and Altman[40] (Fig 2). The limits of agreement were defined as ±1.96*SD, and the 95% CI values for the limits of agreement were identified and are marked in the figures. The Levene test confirmed for the horizontal measurements an increase of the variability of the differences as the magnitude of the measurements increased (P = 0.001) (Fig 2, *C* and *D*). This indicates that for small horizontal measurements the differences were smaller than for large horizontal measurements.

The Pearson correlation coefficient (0.756, P <0.001) between 2 distances (incisal edge-buccal alveolar bone margin and incisal edge-mucogingival junction; n = 48) proved to be moderate, but highly significant. The regression plot between both distances together with the 95% prediction interval is given in Figure 3. The distance from the alveolar bone margin to the mucogingival junction seemed to follow a nearly ideal normal distribution (P = 0.194) around the mean value of 1.67 mm (SD, 1.08; 95% CI, 1.35-1.98) (Fig 4).

DISCUSSION

The rationales behind this investigation were to overcome the deficiencies in the designs of previous studies and to revisit the poorly understood point of anatomic interest of the bony covering in the mandibular front. Yet when comparing our data with those of earlier studies, we were faced with another problem: most previous studies suffer from unsuitable statistical evaluations. Either the authors confined their results to mere descriptive statistics, or the data were assessed by means of correlation analysis. But comparing 2 methods of measurement is "a common abuse of correlation,"[40,44] since the quest is not to analyze the agreement but, rather, the dissimilarity of the 2 measurement methods, and ultimately assess whether the disagreement is small enough to deem the 2 methods interchangeable. Also, the often-assumed approach that considers the physical measures as the "gold standard" might be erroneous.[13] The Bland-Altman method was used to overcome these problems. By applying this method, we were able to

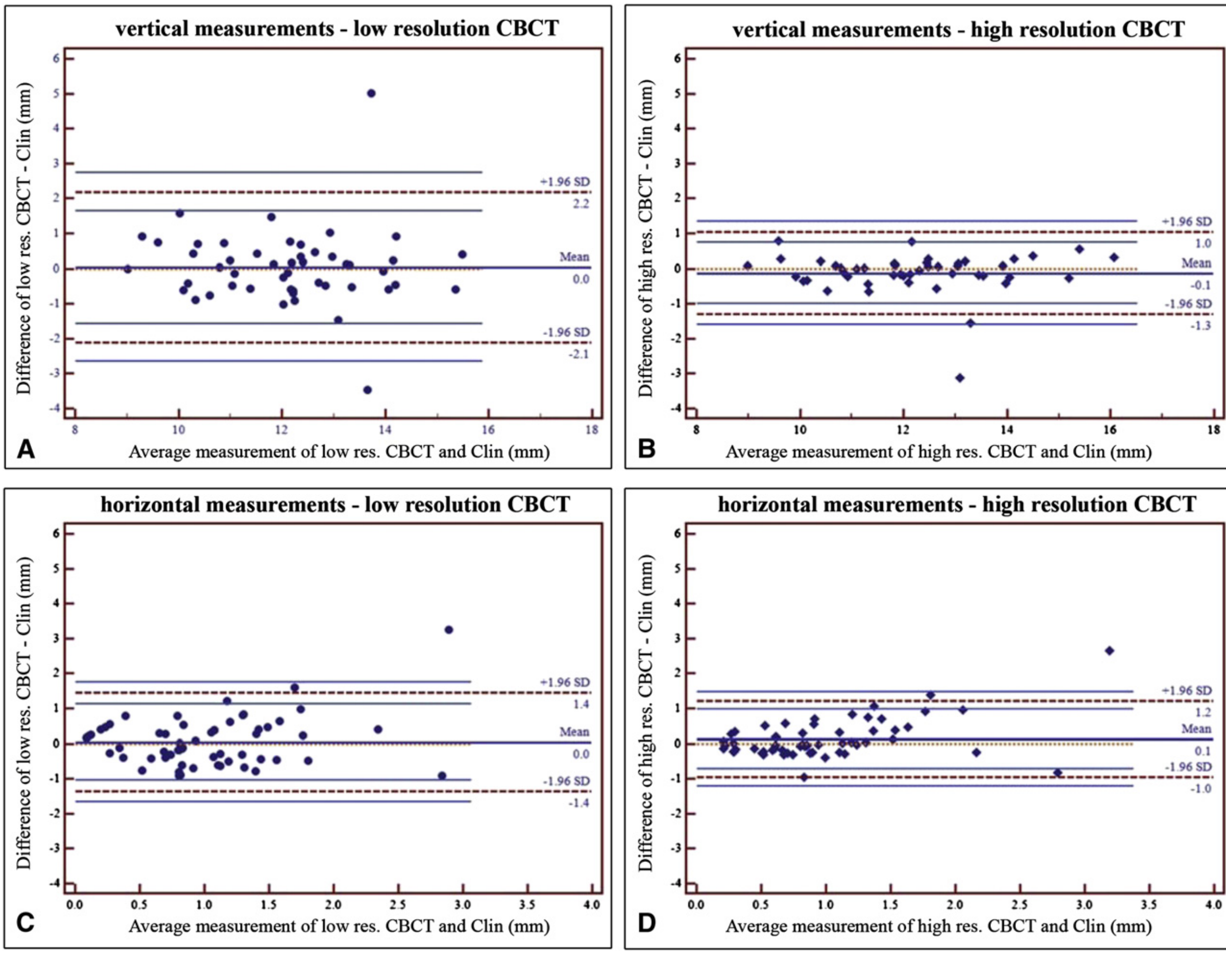

Fig 2. Bland-Altman plots: difference against the mean (*thick solid middle blue line*) of the clinical and radiologic measurements. The limits of agreement (*dashed brown lines*) and the 95% CI of the limits of agreement (*thin solid blue lines*) are shown. Vertical measurements of **A,** low resolution and **B**, high resolution; horizontal measurements of **C**, low resolution and **D**, high resolution. *Circles*, Measurement of the low-resolution protocol; *diamonds*, measurement of the high-resolution protocol; *dotted brown line*, 0.

show the obtained agreement for both vertical and horizontal measurements in the low-resolution and the high-resolution protocols. In the low-resolution protocol, the horizontal measures were somewhat more accurate. The obvious reason is that small absolute measurements were taken when measuring alveolar bone thickness. Taking measurements close to 0 causes the differences of the measurements to be smaller and creates a bias in the limits of agreement. Both the visual interpretation of the plots in Figure 2, *C* and *D*, and the Levene test show that the distribution of the differences is wider as the absolute measurements become larger. This crucial observation and the fact that the limits of agreement are greater than the average thickness of the alveolar bone indicate that both resolution protocols are not accurate enough to measure such delicate structures as the width of the alveolar bone covering.

Our results show that linear measurements of several millimeters made with CBCT of 0.4-mm and 0.125-mm voxel resolutions are accurate. Moreover, our results agree with those of Sun et al,[23] who reported improved accuracy when decreasing the voxel size. Yet, Damstra et al[15] evaluated the accuracy of CBCT on an identical KaVo 3D eXam apparatus at 2 resolutions (0.25-mm and 0.4-mm voxels). Their results showed mean absolute measurement errors of 0.05 mm (±0.04 mm) for the 0.25-mm voxel group and 0.07 mm (±0.05 mm) for the 0.4-mm voxel group. Since there was no tangible difference in accuracy, the authors concluded that the 0.4-mm voxel resolution was adequate for measurements of

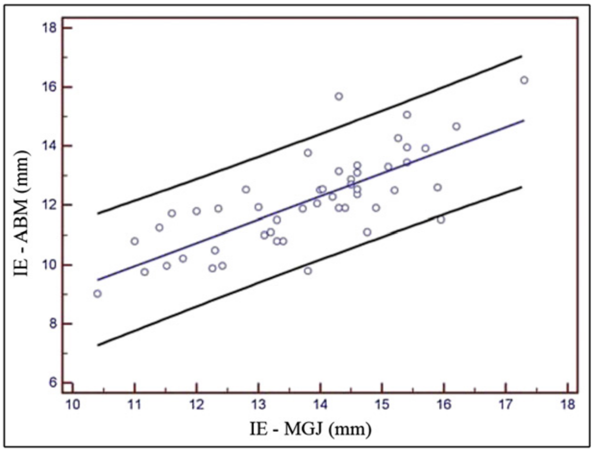

Fig 3. Regression plot for the 2 distances—incisal edge-mucogingival junction and incisal edge-buccal alveolar bone margin—with the 95% prediction interval (*blue line*, Regression line; *bold black lines*, 95% prediction interval; *circles*, clincal measurements).

craniofacial structures. Although there was a difference in methodology in our study (Damstra et al evaluated surface-rendered 3-dimensional models), ours seems to indicate similarly a resemblance in accuracy level for both resolutions in regard to the mean difference. Yet, in light of our findings, the mean difference is not the only aspect that must be evaluated. In the low-resolution protocol, the broader limits of agreement, the greater absolute measurement error, and the wider span of the measurement differences indicate that, although both resolutions are similarly accurate, the low-resolution protocol is less reliably so. In clinical practice, the question should therefore be reformulated; ie, the issue is not primarily how accurate the data should be, but how much inaccuracy is still tolerable in the worst case. Hence, in practice, the decision regarding which voxel size to use should be based on the limits of agreement rather than on the mean value. The finding that a difference between the clinical and radiologic measurements can be as large as 2 mm shows that the average alveolar bone thickness of 1 mm might be missed completely. The limits of agreement in our study give strong evidence to the results of Sun et al,[23] who reported that bone height loss can be overestimated by 1.5 to 2 mm in a 0.4-mm resolution protocol. The established limits of agreement also indicate that, with the voxel resolutions currently available, CBCT cannot be used to determine the bony limits of tooth movement accurately.

Finally, our radiologic measurements are less in accordance with the physical findings than those of Damstra et al,[15] as well as most studies on dry specimens reporting submillimeter accuracy, suggesting that soft tissues do affect the accuracy of bony measures.

Our study also has some noticeable limitations concerning the assessment of accuracy. First, even though intact cadaver heads are probably the closest means to obtain clinical truth, it is still unquestionably an approximation. The lack of noise created normally on radiologic data by the patient's movements probably improved the results, and the alcohol fixation of the specimens might also have had a slight impact on the data. The fixation solution contained low concentrations of glutaraldehyde and formaldehyde, which are known to modify certain tissue properties—eg, a slight muscle expansion and fatty tissue shrinkage[45] by extensive cross-linking[46,47]—and are known to alter periodontal fiber architecture.[48] The second constraint is obvious: using 1 CBCT apparatus does not necessarily reflect the accuracy of other devices. Yet, in 2 patients who had a gingiva flap Herzog et al[49] investigated the accuracy of CBCT measurements of alveolar bone covering with another CBCT device (3D Accuitomo, 0.125-mm voxel size). The similar results (mean difference, 0.092 mm; SD, 0.307 mm) obtained in their study corroborates the assumption that the aforementioned limitation of the use of cadaver heads is clinically negligible. Also, when using identical voxel sizes, the accuracy level of different CBCT devices appears hardly distinguishable.

Another limitation was that only 1 observer measured the data. The bias of only 1 investigator could probably give greater consistency in radiologic landmark identification than the varied interpretations of landmarks by several investigators. According to a meta-analysis on identification and reproducibility of radiologic (cephalometric) landmarks, however, the number of observers does not play a significant role in landmark identification and does not influence the magnitude of the measurement error.[50] On the other hand, one might argue that landmark identification in volumetric data could probably not be compared, since it is unquestionably a more demanding task with a greater likelihood of bias. But in a recent study, de Oliveira et al[51] demonstrated excellent interobserver reliability in CBCT landmark reproducibility in all 3 planes of space.

The alveolar bone covering can be thin. In our specimens, the thinnest bone covering measured was 0.14 mm, but neither did we find relevant dehiscences nor any fenestrations. However, in the radiologic data, there were some sites with absolutely no covering detectable (Fig 5, *B*). Although a thickness difference of 0.14 mm might not be statistically relevant, clinically, the absence or the evidence of bony covering is highly relevant. This important finding also has some ramifications on how to interpret CBCT scans. Previously, Sarikaya

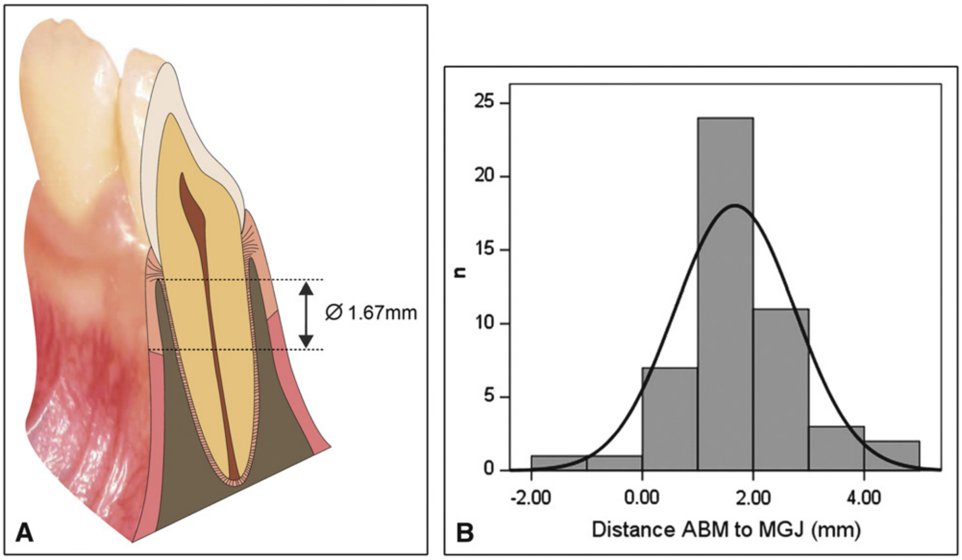

Fig 4. **A**, Graphic illustration of the distance between the alveolar bone margin and the mucogingival junction; **B**, distribution of the distance between the alveolar bone margin and the mucogingival junction. Mean value, 1.67 mm (*black curve*, Normal distribution).

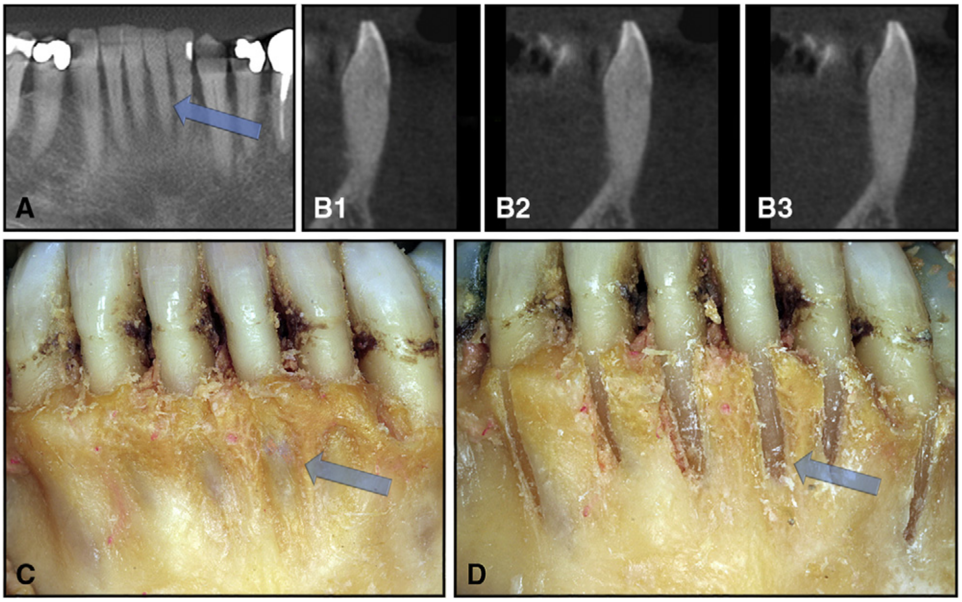

Fig 5. Radiologic data vs clinical findings: mandibular left first incisor as seen on the CBCT scan: **A**, reformatted orthopantomogram view; **B1-B3**, 3 slices in the sagittal view; **C**, clinical views after removing the gingiva; and **D**, after removing the alveolar bone covering. The *blue arrows* in *A*, *C*, and *D* point to the tooth depicted in B1-B3. Note that no bone covering is shown in the sagittal scans (*B1-B3*).

et al[27] examined the alveolar bone thickness on computed tomography scans. Based on their results, they postulated that dehiscences and fenestrations could be identified on computed tomography scans that would be otherwise undetected by cephalograms or clinical examinations. Our study, however, indicates that there is a genuine risk of assuming fenestrations and dehiscences on CBCT radiographs that do not exist clinically. This finding agrees with the observation of Leung et al,[20] who similarly reported that fenestrations are seen 3 times as often on

CBCT scans compared with direct skull examinations. However, they used dry skulls and measured on surface-rendered volumetric 3-dimensional reconstructions. Our study shows that false-positive detections of fenestrations also occur when soft tissue is present. In addition, we demonstrated that a considerably more reliable image display to evaluate CBCT data—sagittal views in multiplanar reformatted images—does not improve the ability to assess fenestrations reliably.

The findings of our study suggest that the undulated course of the mucogingival junction follows the alveolar bone margin in a parallel line. It is reasonable to assume that there is a topographic association between the mucogingival junction and the upper limit of the alveolar bone, since the attached gingiva is connected to the alveolar bone margin through periosteogingival fiber bundles.[52] Yet, this information has probably not been sufficiently appreciated. Most earlier studies that investigated the relationship between the attached gingiva and its bony support focused on the thickness of the keratinized soft tissue rather than on its height.[28,32,53] The height of the attached gingiva is difficult to interpret. Dorfman[29] noticed that the keratinized gingiva can vary in its apicocoronal length, and Ainamo and Talari[54] observed an increase in length related to age. In addition, Wennström[53] wrote that a more lingual position of the tooth results in increased gingival height, but he agreed with the finding of Ainamo and Talari that the mucogingival line is a stable anatomic landmark. It has been recognized that the height of the attached gingiva is influenced by various parameters such as gingival inflammation, dental tipping, and age, whereas the mucogingival junction remains unaffected. We concluded that the vertical position of the alveolar bone is therefore not connected to the height of the attached gingiva, but our results seem to imply that the mucogingival junction reflects somehow the location of the alveolar bone margin. This finding is probably limited to subjects with a healthy periodontium. An inflammation or a severe recession inevitably causes derangement of the fiber bundles and affects the described equilibrium between the attached gingiva and the alveolar bone. Yet, it appears that in healthy patients the mucogingival junction might be an additional aid to locate the alveolar bone margin appropriately.

CONCLUSIONS

1. Both CBCT resolutions provided accurate data and depicted the anatomic truth reliably. CBCT is therefore an appropriate tool for linear intraoral measurements.
2. Voxel size affects the precision of the measurements. The limits of agreement of the different resolution protocols should be considered when choosing the voxel size.
3. There is a genuine risk of overestimating fenestrations and dehiscences on CBCT radiographs, in both the high-resolution and low-resolution protocols. The limits of agreement indicate that an alveolar bone thickness of 1 mm might be missed completely, even with a high-resolution protocol.
4. The presence of soft tissue seems to have a curtailing effect on the accuracy of the CBCT data when determining bony landmarks.
5. The mucogingival junction might be helpful in localizing the alveolar bone margin.

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