Original Article

Evaluation of the Validity of Tooth Size and Arch Width Measurements Using Conventional and Three-dimensional Virtual Orthodontic Models

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Abstract: Measurements and different analyses of dental casts are essential for precise diagnosis of an orthodontic case. At present, virtual computerized models, such as OrthoCAD, are available for clinicians, supplemented by dedicated software for performing needed measurements on them. The purpose of this study was to test the accuracy of measuring casts with the aid of calipers or OrthoCAD and compare these two techniques. Twenty setups using artificial teeth corresponding to various malocclusions were created. Impressions were taken of them, providing 20 plaster and 20 virtual orthodontic models. Measurements of mesiodistal tooth dimension as well as intercanine and intermolar width were made on both. Additionally, values of tooth size were calculated from the isolated artificial teeth removed from the setups and of arch width from the existing setups. The resulting values were compared by the use of nonparametric statistics, and methods' errors were also calculated. Results showed the methods being highly valid and reproducible for both tooth size and arch width. For the tested clinically applicable methods, measurement with digital calipers on plaster models showed the highest accuracy and reproducibility, closely followed by OrthoCAD. Digital calipers seem to be a more suitable instrument for scientific work. However, OrthoCAD's accuracy is clinically acceptable, and most likely, considering its present advantages and future possibilities, the examined or an equivalent 3D virtual models' procedure would become the standard for orthodontic clinical use. (*Angle Orthod* 2003;73:301–306.)

Key Words: Dental models; Diagnostic errors; Observer variation; OrthoCAD; Orthodontics

INTRODUCTION

Successful orthodontic treatment is based on comprehensive diagnosis and treatment planning. A few of the fundamental factors in the diagnosis are the spacing condition, tooth size, arch form and its dimensions, as well as the tooth-arch discrepancies.[1] The model analysis is a time-consuming procedure. Nevertheless, it is a vital part in the diagnosis and subsequent treatment planning process. However, in a day-to-day practice many orthodontists judge the models subjectively, without applying analytical tests.[2,3]

Traditionally, measurements on dental casts are performed with the aid of either Vernier calipers or needle pointed dividers. Shellhart et al[4] concluded in their assessment of the Bolton analysis in crowded dentitions (crowding > three mm), using both the above methods, that a clinically significant measurement error (>1.5 mm) can occur. Alternatively, measurements on photocopies, photos, holograms, or digitization of points from the casts had been proposed,[5–11] but these methods demonstrated errors as well.

Different factors may influence the accuracy and repeatability of measurements of individual teeth within the dental arch. Among these factors are the existing spacing condition, the inclination of the teeth, rotations, presence of interproximal contacts and anatomical variations. Because the need for evidence-based orthodontics is increasing, the accuracy and reproducibility of different measurement methods ought to be evaluated. Otherwise, clinical decisions cannot be justified.

With the ultimate aim of a 'paperless' orthodontic office and with the already existing possibilities of incorporating digital photos and radiographs into the electronic patient's file, the need for replacement of the plaster casts has emerged. Thus, attempts to develop a computerized study model database and analysis have been made. Yamamoto et al,[12] described an optical method for creating 3D com-

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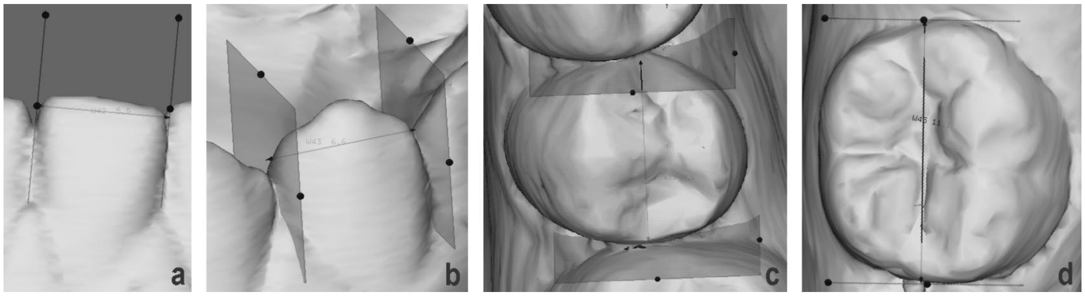

FIGURE 1. Measurements of mesiodistal width of (a) incisor, (b) canine, (c) premolar, and (d) molar using the OrthoCAD tool, as shown from different views.

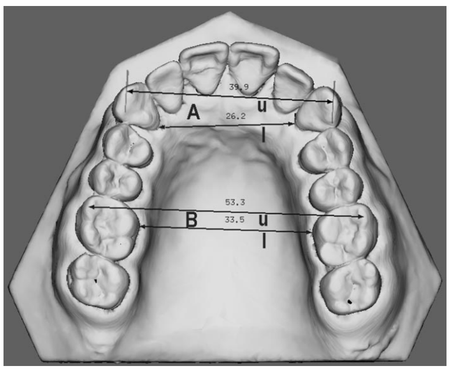

FIGURE 2. Measurements of (A) intercanine and (B) intermolar distances using the OrthoCAD tool. The upper (u) measurements are made between the tip of the cusps, and the lower (l) between the gingival margins of the teeth.

puterized models using a laser beam on a cast. Later other attempts were done to transfer the dental cast into a 3D virtual model[13–18] or even to create an apparatus for intraoral direct scanning.[19] These computerized models are the platform for calculating distances by using designated software and estimating treatment effects and tooth movements in this way. OrthoCAD is such a system that is commercially available and provides the possibility of transforming impressions or plaster casts into 3D virtual models.[20]

The idea of 3D virtual orthodontic models seems very promising, if proven to be accurate and trustful. The electronic storage of all patient's information, including study casts, will eliminate problems of storage, retrieval and maintenance of models, office management and communication between different specialties giving the possibility for easier consultation. This alternative will make everyday work more efficient and will appeal to the patients as up-to-date dental care.

However, the performance of 3D virtual models for validity and reproducibility has not been thoroughly studied, apart from the Bolton ratio.[21] Tomassetti et al[21] evaluated different measuring methods, including OrthoCAD, to calculate the Bolton tooth size analysis. OrthoCAD's values were found to be less correlated to the baseline values established by the average of three repeated measurements using Vernier calipers, than the values of the computerized digital calipers' method (Hamilton Arch Tooth System).

Therefore, the purpose of the present study was to test the accuracy of the conventional measuring method using calipers to test the OrthoCAD-based measurement tool and to compare these two methods, assuming that they demonstrate similar accuracy.

MATERIALS AND METHODS

Setups, simulating various types of malocclusion with different degrees of rotation and inclination of teeth, variety of spacing condition and curve of Spee depths, were constructed. By using 10 sets of artificial teeth more than once, 20 setups were created. These setups were duplicated using alginate (Algiflex green fast, Svedia dental, Enköping, Sweden), resulting in 20 corresponding dental stone models (Fujirock® EP, type 4 dental stone, GC, Tokyo, Japan). Impressions were taken again from the setups with addition type silicone (putty—Provil® novo soft fast set, and wash—Provil® novo light C.D. fast set, Heraeus Kultzer, Hanau) using a two-step putty wash impression technique and sent to OrthoCAD (Cadent Inc, Fairview, NJ), to be transformed into 20 3D virtual models.

The tooth size, intercanine and intermolar arch width were examined. The same investigator performed tooth size measurements of mesiodistal crown width in the following manner (Figure 1).

1. At every isolated artificial tooth, after being removed from its setup, with the aid of an electronic caliper (Digital 6, Mauser, Winterthur, Switzerland) with accuracy of 0.01 mm (method A).
2. On the plaster models, using the same electronic calipers (method B).
3. On the computerized models, using the OrthoCAD measurement tools (version 1.17) with accuracy of 0.1 mm (method C).

Measurements of arch width were performed on six of the setups, on the plaster, and on the computerized models. The upper and lower intercanine and intermolar widths were measured (Figure 2).

TABLE 1. Random Errors (Absolute Values in mm) Calculated for the Mesiodistal Width of the Different Teeth Groups as Well as for the Intercanine and Intermolar Width Measurements for All Investigated Methods

	Incisors	Canines	Premolars	Molars	Arch widths
Teeth (mm)	n = 16	n = 8	n = 16	n = 8	
Intraobserver error	0.0264	0.0272	0.0260	0.0478	
Interobserver error	0.0344	0.0377	0.0348	0.0720	
Casts (mm)	n = 38	n = 20	n = 40	n = 20	n = 40
Intraobserver error	0.0549	0.0635	0.0598	0.0783	0.1815
Interobserver error	0.0650	0.0678	0.0992	0.1221	0.2187
Orthocad (mm)	n = 40	n = 20	n = 40	n = 20	n = 40
Intraobserver error	0.0742	0.0725	0.0775	0.1173	0.2031
Interobserver error	0.0793	0.0873	0.1041	0.1390	0.2465

TABLE 2. Systematic Error Values (in mm) Found to be Statistically Significant ($P < 5\%$), Established on the Differences Between Repeated Measurements

	SE	SD	Mean	*P*-value
Casts (mm)				
Interobserver error				
Canines (n = 20)	−0.055	0.0826	0.0185	.011
Molars (n = 20)	−0.095	0.143	0.032	.016
Orthocad (mm)				
Intraobserver error				
Molars (n = 20)	0.125	0.112	0.025	<.001
Interobserver error				
Premolars (n = 40)	−0.0625	0.148	0.0234	.007
Molars (n = 20)	0.15	0.15	0.0336	<.001
Widths (n = 40)	0.117	0.349	0.0552	.04

The teeth width database was further divided and investigated according to the different teeth groups: central and lateral incisors (incisors' group), canines (canines' group), first and second premolars (premolars' group), and first molars (molars' group).

To establish the same resolution for all methods before their comparison, all values were rounded to the nearest 0.1 mm. Because of the severe malalignment of teeth that were arranged and because of the properties of the impression material, some of the teeth broke or were badly damaged. Therefore, in the final analysis three teeth (two incisors and one canine) as well as three arch widths (one upper and two lower distances) were excluded from the measurements.

Statistics

Statistical analyses were applied to investigate the usability of the described techniques, with the aid of the statistical program SigmaStat for Windows v. 2.0.

The normality of distribution failed for many measured variables, which could be explained by the use of the same sets of teeth more than once, resulting in a noticeably skewed distribution. Consequently, Kruskal-Wallis one-way analysis of variance on ranks as well as Pearson product moment correlation and linear regression were applied concerning the teeth size, which were evaluated separately for every group of teeth (incisors, canines, premolars, and molars). The abovementioned statistical analyses with the addition of Mann-Whitney rank sum test were applied to the values of the intercanine and intermolar widths, which were evaluated separately for the upper and lower measurements (Figure 2).

Estimation of method error

Both intra- and interobserver errors were evaluated. For the evaluation of the intraobserver error, four sets of teeth, ten plaster and ten 3D virtual models were measured twice after an interval of at least two weeks.

For the interobserver error, a second investigator measured the same four sets of teeth, ten plaster and ten 3D virtual models twice, and the mean values of the two measurements by each investigator were compared. To calibrate the two investigators[22] to a uniform measuring method, all measurements were performed only after mutual instruction and training were performed.

The random and systematic errors were calculated by using the formula described by Dahlberg[23]

$$\left(S_i = \pm\sqrt{\frac{\sum d^2}{2n}}\right)$$

and by Houston[24]

$$[t = (\bar{x}\sqrt{n})/s]$$

respectively. Both the random (Table 1) and systematic error were found to be very small and clinically insignificant, though some systemic errors were found statistically significant at the level of 5% (Table 2), absolute differences were clinically insignificant as well.

RESULTS

When the teeth widths were compared between all three methods, all measurements were highly correlated. For all teeth groups, measurements carried out using methods A and B exhibited the highest correlation ($R = 0.929$–0.998), followed closely by both method C to method A values ($R = 0.784$–0.976), and method C to method B measurements

TABLE 3. Statistical Analysis of Mesiodistal Tooth Width Measurements. Kruskal-Wallis One-Way Analysis of Variance on Ranks and Pearson Product Moment Correlation Were Used for the Comparison of All Investigated Methods

	Median	25%	75%	Kruskal-Wallis test (*P* value)	Method	Pearson correlation
Incisors (n = 78)						
Method A[a] (mm)	6.3	5.2	8.1		A-B	0.998
Method B[b] (mm)	6.3	5.2	8.0	0.687	A-C	0.976
Method C[c] (mm)	6.6	5.4	8.0		B-C	0.975
Canines (n = 39)						
Method A (mm)	7.6	6.8	7.8		A-B	0.977
Method B (mm)	7.6	6.8	7.9	0.809	A-C	0.859
Method C (mm)	7.4	6.7	8.0		B-C	0.827
Premolars (n = 80)						
Method A (mm)	6.7	6.4	7.3		A-B	0.929
Method B (mm)	6.7	6.5	7.2	0.410	A-C	0.784
Method C (mm)	6.8	6.5	7.2		B-C	0.763
Molars (n = 40)						
Method A (mm)	10.8	10.2	11.3		A-B	0.949
Method B (mm)	10.7	10.2	11.4	0.982	A-C	0.845
Method C (mm)	10.8	10.2	11.3		B-C	0.849

[a] Measurements performed on isolated teeth removed from setups.
[b] Measurements performed on teeth at the plaster models.
[c] Measurements performed on the teeth at the computerized models.

(R = 0.763–0.975) (Table 3). This is also illustrated in Figure 3, where the scatter of the values of incisors' size retrieved from the three methods is shown.

When the intercanine and intermolar widths were compared, at both the gingival margin (lower measurement) and cusp tip sites (upper measurement), high correlation values were found with all methods (R = 0.998–1) (Table 4).

DISCUSSION

Within a confidence interval of 95%, we could not prove that measurements carried out with the three methods differed from each other. Measurements made directly on cast with electronic calipers were found to be the most accurate and repeatable. By the use of this method, the highest regression coefficient values in all groups as well as the smallest inter- and intraobserver errors were exhibited. Nevertheless, OrthoCAD showed good correlation and small inter- and intraobserver error as well (Tables 1–4). In the comparison between methods A, B, and C, none of the tested groups (incisors, canines, premolars, and molars) demonstrated statistically significant differences (Table 3).

One hidden assumption in this study is that measurement of isolated teeth is the most accurate method. Consequently, the regression coefficient of the tested methods as determined to the isolated tooth values (method A) was considered more important than to each other. As seen in Table 3, the regression coefficient of OrthoCAD was similar in comparison with measurement with digital calipers on isolated teeth or on casts.

In the following, our discussion will be mostly focused on the differences between method B and C because method A is not clinically feasible. Because the mesiodistal width of teeth is used to calculate Bolton's ratio,[25,26] results concerning tooth widths could be compared with results regarding Bolton's ratio. Thus, our results are indirectly in agreement with Tomassetti et al.[21] They compared the accuracy of four different measuring systems concerning Bolton's ratio and concluded that measurements based on Vernier calipers were the closest to a baseline, established as the mean of three repeated measurements using conventional calipers. OrthoCAD (version 1.14) was the second most accurate method. However, a disparity regarding the level of inaccuracy was noticed between these studies. This could be attributed to the following factors:

1. In the present study great attention was given to the detailed design regarding materials and means used:
   - Polyvinylsiloxane was the impression material for the 3D virtual models instead of alginate.
   - Dental stone with small expansion factor (0.08%) was used.
   - Digital caliper with accuracy of 0.01 mm was the instrument for the measurements instead of traditional ones.
   - Measurements were performed on isolated teeth instead of models.

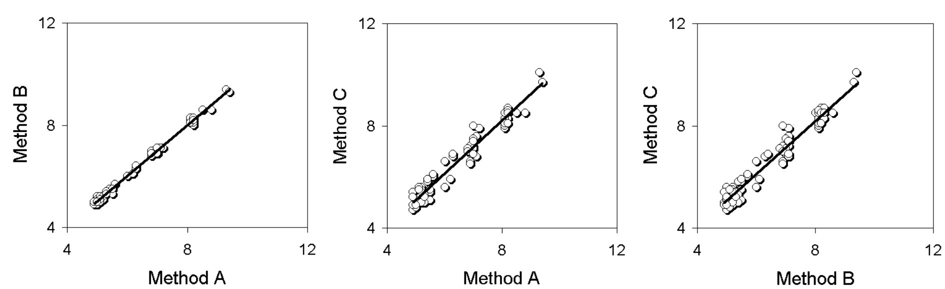

FIGURE 3. Scatter graph illustrating the regressions between methods A, B, and C, concerning the incisors' width (n = 78). Method A, measurements performed on isolated teeth removed from setups. Method B, measurements performed on the teeth at the plaster models. Method C, measurements performed on the teeth at the computerized models.

TABLE 4. Statistical Analysis of Intercanine and Intermolar Arch Width Measured on Teeth' Tips (Upper Measurement) and on their Gingival Margin (Lower Measurement). Kruskal-Wallis One-Way Analysis of Variance on Ranks, Mann-Whitney Rank Sum Test as Well as Pearson Product Moment Correlation Were Used for the Comparison of All Investigated Methods

	Median	25%	75%	Kruskal-Wallis test (*P* value)	Mann-Whitney test (*P* value)	Methods' comparison	Pearson correlation
Upper measurement (n = 12)							
Method A′[a] (mm)	38.9	28.2	46.0			A′-B	0.999
Method B[b] (mm)	38.6	28.4	46.3	0.987		A′-C	0.998
Method C[c] (mm)	39.0	28.1	46.8			B-C	0.998
(n = 39)							
Method B (mm)	40.9	29.4	47.2		0.956	B-C	0.998
Method C (mm)	40.8	29.8	48.2				
Lower measurement (n = 12)							
Method A′ (mm)	28.7	20.8	33.3			A′-B	1
Method B (mm)	28.4	20.4	33.0	0.773		A′-C	0.999
Method C (mm)	28.9	21.1	33.6			B-C	0.998
(n = 38)							
Method B (mm)	28.1	21.1	34.1		0.593	B-C	0.997
Method C (mm)	29.2	21.3	34.6				

[a] Measurements performed on the setups.
[b] Measurements performed on the plaster models.
[c] Measurements performed on the computerized models.

- A later version of OrthoCAD software (1.17) was available, where the tooth width is measured as a distance between two selected and adjustable parallel planes tangent to the contact points, instead of a distance between two selected contact points.

2. In this study an effort was made to make the measurements as accurate as possible with less attention to the time spent for measuring. On the other hand, Tomassetti et al[21] put an emphasis on a more clinical approach, where the time spent on each model was measured. This could have hampered the results by compromising accuracy.
3. Moreover, in the Tomassetti et al study, the error of the method was not investigated concerning OrthoCAD.

In the present study, the greatest difference found in the premolar group could be attributed to crowding, usually pronounced in the posterior regions of the setups. Systematic error was found to be relatively high in the molar group in method C, which could be due to the special morphology of these teeth, in particular of the upper molars.

Another factor that could be elucidative in the superiority of method B regarding accuracy is the special characteristics of computerized 3D models. Even though OrthoCAD is a real 3D model, the image viewed is only two-dimensional. Thus, identification of points, axes and planes becomes more difficult. This might have hampered the results of OrthoCAD regarding validity, reproducibility, and consumed time needed for the selection of points. Therefore, it was very important for the observers to get familiar with the methods, especially because the investigators were not familiar with OrthoCAD before the study.

Concerning the arch widths, similar results were found exhibiting better correlation but slightly bigger method errors. This is partly because arch width measurements were bigger than tooth width values, resulting in relatively smaller deviations, even if the absolute differences were higher.

A question that arises is whether these results, emerging from a research situation are applicable to a clinical setting. For example, will the results be similar if alginate is used, or whether taking impressions from the oral cavity will alter the result as well?

Additionally, the present study did not allow us to answer whether a digital model constructed using a nondestructive technique will give more accurate measurements when compared with controls than a digital model constructed with a destructive technique.

The computerized system seems as to be a very attractive clinical solution, as because it has the advantage of storing study model information in an electronic format, which would benefit the orthodontist from both the management and marketing perspectives. In order fFor a programs to be accepted by orthodontists, it hasthey also have to be accurate and clinically efficient in terms of ease of use and time consumed for its their operation. On the other hand, for research purposes the requirements are different and concentrate more on the accuracy of the method. When evaluating OrthoCAD regarding these criteria, it seems that it is still inferior to the conventional method of cast measurements by digital calipers, and probably to measurements performed with the use of an optical or laser beam. Therefore the examined 3-D virtual models seem appropriate as a clinical tool, but inferior as a research tool.

A main difficulty for the non-American orthodontists to incorporate the virtual models into practice is the current absence of centers outside the U.S.A.nited States for the transformation of impressions into 3D models. This was one reason that a more expensive, but less sensitive to time-dependent deformation, impression material was used.

Nevertheless, a continuous development is foreseen as more suppliers of these services are emerging (OrthoCAD[27], E-models[28]) which could eventually result in possible new applications. Such applications could include dental set-ups, automatic recognition of points and calculation of measurements, radiographic mensuration, treatment and surgical planning, evaluation of treatment results, forensic use, digital bracket positioning, and direct intraoral scanning.

CONCLUSIONS

Considering this to be a valid method, for evaluating tooth width and arch width on the setups, the conclusions can be described as follows:

- Measurement with digital calipers on plaster models produced the most accurate and reproducible results.
- The OrthoCAD measurement tool showed high accuracy and reproducibility but was inferior to measurements done on plaster models with digital calipers.
- Digital calipers seem to be a more suitable instrument for scientific work. However, OrthoCAD's accuracy is clinically acceptable, and it is likely, taking into consideration its present advantages and future possibilities, that the examined or an equivalent 3D virtual model procedure would become the day-to-day standard for orthodontic use.

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