DOI: 10.2478/aoj-2012-0004

Validity and reliability of tooth size and dental arch measurements: a stereo photogrammetric study

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Background: The development of three-dimensional computer imaging has many applications in dentistry, including the analysis of dental casts.

Aims: To assess the validity and reliability of a dental stereophotogrammetric imaging system.

Methods: The sample consisted of 35 sets of dental casts. Maxillary and mandibular dental crown widths and selected dental arch dimensions were measured directly using digital calipers. Cast images were also captured by a stereophotogrammetric system and analysed using Australis software. Dahlberg's formula, paired *t*-tests and intra-class correlations were used to assess the random error, validity and reliability of the measurements, respectively.

Results: Most values demonstrated no significant difference between the direct and three-dimensional measurements with mean differences ranging from 0.05 - 0.21 mm. Moreover, values of intra-class correlation coefficients ranged between 0.80 - 0.99 for intra-examiner reliability.

Conclusions: Mesiodistal crown widths and dental arch dimensions may be measured accurately with relatively small error by the specially-designed 3D system and confirms its suitability for clinical and research purposes.

(Aust Orthod J 2012: 22-29)

Received for publication: February 2011
Accepted: Accepted February 2012

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Introduction

Dental casts have been used in clinical practice and research for many years and possess several advantages related to cost, ease of production and manipulation.[1] However, problems of transferability of dental casts, their storage and maintenance, in addition to their risk of damage have been recognised.[2]

Several attempts have been made to replace dental casts by using two dimensional (2D) images obtained with standardised cameras,[3] but deficiencies have been noted related to inaccuracy.[4,5] With advances in computer technology, various methods of three-dimensional (3D) dental cast imaging have been developed.[5] Bell et al.[2] assessed the usefulness and validity of a stereophotogrammetric system and found that errors were minimal and between 0.10 - 0.48 mm.

Zilberman et al.[7] and Goonewardene[8] utilised OrthoCAD technology to assess the validity and reliability of dental measurements (Cadent, Fairview, NJ, USA) and concluded that the technique was accurate and reproducible. In addition, further studies determined that the mean differences between direct measurements and those obtained from 3D images of dental casts tended to be less than 0.5 mm, even though arch lengths and tooth sizes appeared to be consistently larger when digital models were used.[9]

A specially-designed 3D imaging system has been developed with the collaboration of the Universiti

Sains Malaysia and the Universiti Teknologi Malaysia. The purpose of the present study was to test the validity and reliability of selected dental cast measurements using a 3D imaging system and to compare the findings with direct caliper measurements.

Materials and methods

The sample size (N) for this study was calculated based on comparisons with paired *t*-tests. Alpha was set at 0.001 and experimental power was set at 80 per cent with a detectable difference of 0.5 mm and a SD of 0.62 mm. The calculated sample size was 38, but three subjects withdrew and the final number of participants reduced to 35.

Seventy dental casts of the 35 participants from the Health Campus of the Universiti Sains Malaysia, Kota Bharu, Malaysia were included in this study, according to the following criteria: a full set of permanent teeth except third molars and normal crown shape with no carious lesions or restorations. Dental impressions were obtained of the upper and lower dental arches. Alginate impression material was handled by a single investigator according to the manufacturer's instructions (Kramopan, Italy). All impressions were obtained by a single investigator (ARK). To minimise possible distortion, impressions were poured immediately with dental diestone (Calstone, France). The study was approved by the Human Ethics Research Committee at the Universiti Sains Malaysia [No.156.4 (5) 2008].

Dental imaging system

The stereophotogrammetric system consisted of two digital cameras (Sony Electronics, Japan) mounted together on an adjustable holder and simultaneously triggered by a remote control switch (Graphic Media Research, MN, USA) as shown in Figure 1. The photogrammetric control frame contained 55 well-distributed control points with 3 mm reflective retro-targets arranged in grid form.

Before data acquisition, calibration procedures were performed to ensure 3D measurement accuracy. The procedures were divided into camera and control frame calibrations and conducted to determine camera parameters.[10,11] Camera position was adjusted to be 450 mm away from a highly precise and previously calibrated board. This distance reflected the camera-object distance of the stereo photographic system. After capturing each image, the target board was rotated 90 degrees to enable four photographs to be taken. In addition, the camera was rotated around its z axis by 90 degrees to allow for four more convergent photographs.[12-14] The calibration of the control frame required a set of eight convergent photographs taken by a previously calibrated camera.[12-14] The coordinate position was detected in each retro-target point for each image. A bundle adjustment process was run to determine the coordinates of the signalised targets.[10] Australis camera calibration software (6.06, Photometrix Pty Ltd., Australia) was applied to calculate camera parameters.[15]

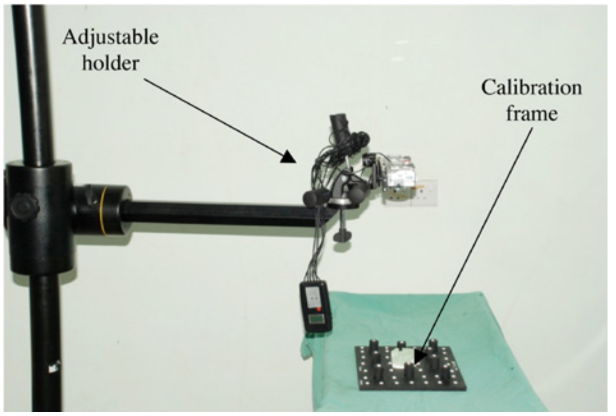

Figure 1. Dental cast stereophotogrammetric system shows stereo camera, synchronisation switch, calibration frame and adjustable cameras' holder.

Data processing and analysis

Each landmark on right and left images of each view was magnified until it was accurately seen on the computer screen and digitised using the manual mode (Figure 2). The cursor was positioned over the landmark, the mouse was clicked and the point produced as a numbered cross on the image. The same procedure was followed for all landmarks. When cast digitisation was completed, an automatic triangulation was conducted, following which the 3D coordinates and the measurable distances were displayed.

Maximum mesiodistal crown dimensions were measured from the occlusal surfaces and parallel to the occlusal plane. The measurements were obtained between the points that represented the anatomical contact points or where it was considered that normal contact should have occurred with the neighbouring tooth.[16]

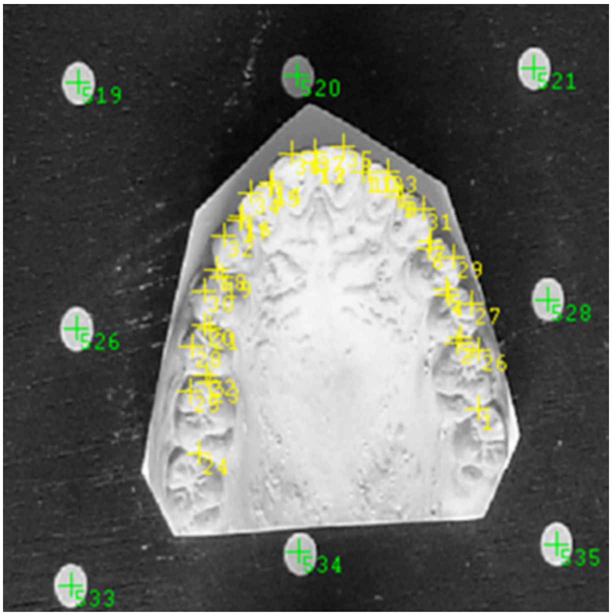

Figure 2. Image of study cast shows the automatic landmark digitisation of the calibration frame and the anatomical points after digitisation.

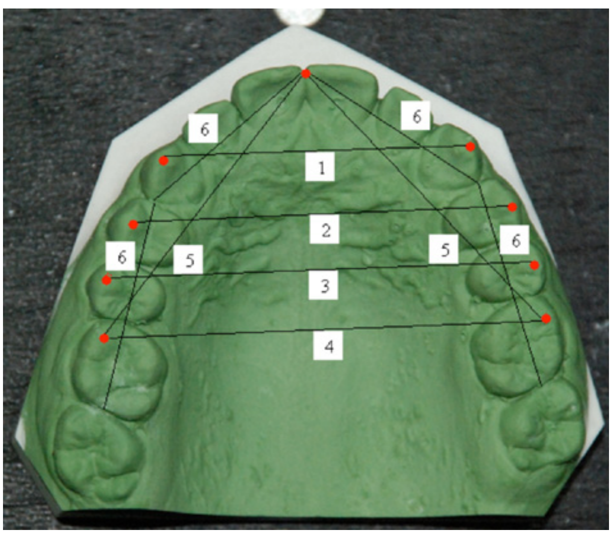

Figure 3. Dental arch dimensions on the dental cast including intercanine (1), inter-first premolar (2), inter-second premolar (3), intermolar (4), arch length (5) and arch perimeter (6).

Dental arch dimensions were defined by several parameters.[17-19] The intercanine distance was the distance between cusp tips of the deciduous and permanent canines, the inter-premolar distance was the distance between buccal cusp tips of the right and left maxillary and mandibular first premolars and the intermolar distance was the distance between the mesiobuccal cusp tip of the right and left maxillary and mandibular permanent first molars. Arch length was defined as the diagonal line between the mesiobuccal cusp tip of the first molar and the mesial contact areas of the central incisors. Dental arch perimeter was represented by four bilateral segments. The first segment was represented by the distance between the distal contact point of the first molar and the distal contact point of the canine. The second segment was represented by the distance from the distal contact point of the canine and the mesial contact point of the central incisor. The same distances were measured on the opposite side (Figure 3).

The imaging protocol of the dental casts was performed and relevant distances on the dental casts were measured on the computer screen. Arch dimensions and mesiodistal crown dimensions were also measured using digital calipers (Mitutoyo, Japan) to the accuracy of 0.1 mm. After a minimum period of 24 hours, 3D cast image acquisition and analysis were repeated by the same investigator (ARK) to determine the intra-examiner reliability for each study variable.

According to Houston,[20] validity (or accuracy) is defined as the extent to which the value obtained represents the object of interest, whereas reliability is defined as the closeness of successive measurements of the same object.[20-21] Dahlberg's formula, paired *t*-tests and the intra-class correlation coefficients (ICC) were computed to assess the random error, validity and reliability for the 3D image versus the dental cast and for the 3D intra-examiner measurements.[3,20-22] Because 38 variables were included and many different significance tests were performed, Bonferroni correction was applied to avoid inflated type I error. After adjustment, results were considered significant only if $p < 0 .001$ (0.05/38).

Results

The results for the random error, variability and reliability of the mesiodistal crown widths and the arch dimensions derived using the 3D system are presented in Tables I and II, respectively. The average random error observed for dental cast versus 3D measurements was 0.27 mm, with a range of 0.17 - 0.42 mm for mesiodistal crown widths and 0.13 - 0.58 mm for dental arch dimensions. The mean differences between direct and 3D measurements ranged between 0.07 - 0.21 mm for tooth size and 0.05 - 0.17 mm for dental arch dimensions. Most of these differences were not statistically significant; however, variables involving second premolars, canines and arch perimeter displayed

Table I. Comparison of measurements of mesiodistal crown widths between digital images and calipers.

Variable (mm)	Difference		ICC		Dahlberg	
	Right	Left	Right	Left	Right	Left
Upper dental arch						
First molar	0.09	0.12*	0.89*	0.91*	0.27	0.26
Second premolar	0.11*	0.09	0.83*	0.97*	0.25	0.26
First premolar	0.07	0.13*	0.96*	0.89*	0.17	0.25
Canine	0.19*	0.21	0.97*	0.75*	0.19	0.42
Lateral incisor	0.09	0.10	0.92*	0.94*	0.20	0.22
Central incisor	0.10	0.13	0.88*	0.88*	0.29	0.32
Lower dental arch						
First molar	0.10	0.08	0.86*	0.88*	0.26	0.24
Second premolar	0.10	0.10*	0.89*	0.96*	0.22	0.19
First premolar	0.09	0.09	0.93*	0.83*	0.22	0.37
Canine	0.13*	0.19*	0.86*	0.83*	0.25	0.31
Lateral incisor	0.07	0.14	0.87*	0.87*	0.22	0.40
Central incisor	0.13*	0.10	0.81*	0.92*	0.28	0.21

* Significant at $p < 0.001$

Table II. Comparison of measurements of dental arch dimensions between digital images and calipers.

Variable (mm)	Difference	ICC	Dahlberg
Upper dental arch			
Intermolar	0.06	0.99*	0.36
Inter-second premolar	0.08	0.99*	0.37
Inter-first premolar	0.08	0.98*	0.37
Intercanine	0.05	0.96*	0.36
Right arch length	0.10	0.99*	0.41
Left arch length	0.07	0.97*	0.47
Arch perimeter	0.12*	0.95*	0.58
Lower dental arch			
Intermolar	0.06	0.99*	0.17
Inter-second premolar	0.05	0.99*	0.28
Inter-first premolar	0.07	0.99*	0.17
Intercanine	0.06	0.99*	0.13
Right arch length	0.14*	0.93*	0.29
Left arch length	0.11	0.99*	0.29
Arch perimeter	0.17*	0.94*	0.31

* Significant at $p < 0.001$

statistically significant differences in measurements between the caliper and 3D system. The smallest difference in mesiodistal crown width was recorded for the right upper first premolar and lower right lateral incisor, whereas the greatest difference was recorded for the upper left canine. Arch dimension analysis revealed that the upper intercanine, lower inter-second premolar distances recorded the lowest differences, whereas arch perimeter measurement recorded the highest difference. The intra-class correlation coefficients were generally high and ranged between 0.81 - 0.96 for the crown widths and 0.94 - 0.99 for the arch dimensions.

The 3D intra-examiner results are presented in Tables III and IV. Random error analysis for the 3D readings on two different occasions ranged between 0.16 to 0.27 mm for tooth width and dental arch dimensions. Paired *t*-tests indicated eight significant differences. The highest difference was recorded for the upper left central incisor and the lowest value for the upper right first molar. The average ICC was 0.88 for crown widths and 0.97 for dental arch dimensions. The highest ICC value for mesiodistal crown width was recorded for the upper and lower left second premolars and the lowest by the lower left central incisor. For the dental arch dimensions, the highest ICC was recorded for intermolar distance and the lowest for lower intercanine distance.

Discussion

The present study has provided a comprehensive analysis of the validity and reliability of selected mesiodistal crown widths and arch dimensions generated by a specially-designed 3D photogrammetric system. This system relied on stereophotogrammetric principles to create and extract 3D data from dental casts and to allow storage in a digital format.

All measurements were obtained from the occlusal surface as this appears to be the best method for ensuring validity, reliability and speed of operation.[24] A single operator carried out all of the measurements and therefore only intra-examiner differences were assessed. On average, most of the measurable values displayed a high degree of validity. The mean difference between caliper and 3D measurements was below 0.5 mm. Although statistically significant differences were found in several variables, the actual differences were small and unlikely to be of clinical significance. Several studies have argued that variations of less than 0.5 mm in tooth size fall within the expected range of measurement error and should not affect treatment planning.[2,25,26]

A comparison between the 3D image calipers produced a random error which appeared to be within acceptable limits. However, the validity and reliability of the different variables was mixed as some appeared more accurate and reliable than others. Measurements of intermolar width were most accurate, whereas those for lower arch length, mesiodistal crown diameters of anterior teeth, particularly the upper left canine, were found to be less accurate and reliable. Previous studies have reported variable results for validity of measurements obtained using 3D systems compared with direct manual measurements. Bell et al.[2] recorded discrepancies of 0.1 - 0.48 mm in their stereophotogrammetric system, whereas, Santoro et al.[6] reported a range of 0.16 - 0.38 mm, and Stevens et al.[26] described a range of 0.04 - 0.83 mm for the OrthoCAD system. The present study reported findings which differed from those of Asquita et al.[27] who measured differences greater than 0.62 mm for upper intermolar distances. These differences were regarded as clinically insignificant. Asquita et al. further found that measurements of intercanine width were most accurate and reliable but those for upper arch length and lower premolar mesiodistal width were least accurate and reliable. However, direct comparisons with these studies should be made with caution due to differences in the methodology used. The validity and reliability of mesiodistal measurements may be influenced by the inclination, rotation and anatomic variations of the teeth, and even caliper position.[2,9]

In the present study, the 3D intra-examiner measurements showed an excellent degree of reliability according to the criteria used by Roberts and Richmond.[28] The recorded differences between the measurements obtained on two occasions could be due to the potential variation in location of the mesiodistal landmarks. This difference was considered clinically minimal.[2] Brook et al.[23] recorded that discrepancies less than 0.4 mm between successive recordings may be considered insignificant when assessing intra-examiner differences.

The present results support those of Zilberman et al.[7] and Goonewardene et al.[8] who reported good and excellent correlations for intra-examiner reliability.

Table III. Comparison of measurements of mesiodistal crown widths between first and second digital image readings.

Variable (mm)	Difference		ICC		Dahlberg	
	Right	Left	Right	Left	Right	Left
Upper dental arch						
First molar	0.05	0.12	0.87*	0.93*	0.21	0.21
Second premolar	0.15*	0.18*	0.91*	0.96*	0.18	0.21
First premolar	0.10	0.18*	0.94*	0.95*	0.15	0.18
Canine	0.03	0.13	0.81*	0.85*	0.25	0.28
Lateral incisor	0.16	0.24	0.80*	0.84*	0.26	0.33
Central incisor	0.06	0.25*	0.92*	0.91*	0.18	0.28
Lower dental arch						
First molar	0.15*	0.15	0.93*	0.85*	0.18	0.21
Second premolar	0.17*	0.06	0.90*	0.96*	0.20	0.15
First premolar	0.12	0.21*	0.93*	0.92*	0.19	0.20
Canine	0.13	0.18	0.85*	0.83*	0.22	0.33
Lateral incisor	0.17	0.11	0.85*	0.89*	0.25	0.18
Central incisor	0.16	0.18	0.85*	0.80*	0.21	0.27

* Significant at $p < 0.001$

Table IV. Comparison of measurements of dental arch dimensions between first and second digital image readings.

Variable (mm)	Difference	ICC	Dahlberg
Upper dental arch			
Intermolar	0.07	0.99*	0.24
Inter-second premolar	0.26*	0.98*	0.24
Inter-first premolar	0.05	0.98*	0.22
Intercanine	0.07	0.91*	0.29
Right arch length	0.06	0.97*	0.28
Left arch length	0.10	0.96*	0.23
Arch perimeter	0.12	0.96*	0.37
Lower dental arch			
Intermolar	0.11	0.99*	0.23
Inter-second premolar	0.16	0.97*	0.22
Inter-first premolar	0.08	0.99*	0.16
Intercanine	0.12	0.85*	0.27
Right arch length	0.25*	0.98*	0.28
Left arch length	0.14	0.97*	0.27
Arch perimeter	0.16	0.97*	0.36

* Significant at $p < 0.001$

Hunter and Priest[16] noted that measurement technique may depend upon tooth position and reported that investigators were inconsistent in their interpretation of canine measurements. Furthermore, intra- and inter-examiner variability was greater for posterior teeth.

It was found that the 3D system used in the present study tended to slightly overestimate actual measurements. This was most likely due to the ability to magnify the image, or due to difficulties in accurately measuring in the region of the contact points.[24-25] In contradistinction, Stevens et al.[26] were unable to identify consistent tooth width differences with digital models. Nevertheless, the range of differences between direct and 3D measurements was similar in both studies and unlikely to be clinically significant. Stevens and colleagues considered the possible differences in results between direct and indirect methods were attributed to the distortions in the fabrication process between the impressions and the 3D models, to operator differences when clicking the mouse on tooth locations and to differences in model details around tooth borders or contact points.[26] Santoro et al.[6] found that digital measurements tended to be smaller than manual measurements and suggested that alginate shrinkage during transportation to the OrthoCAD location and different pouring times might be a possible explanation.

Bell et al.[2] stated that there will always be differences between direct and 3D measurements due to variations in the manual positioning of measuring calipers, even when measuring points are clearly marked. In addition, Asquith et al.[27] noted that during the measurement of dental casts, the sharpened points of the calipers may cause wear of the casts and this may affect repeated measurements of mesiodistal tooth width. Indeed, a clinician's training and abilities can influence measurement validity and reliability with both the traditional direct or computer screen methods of measurement.[6-8]

After intensive training, the measurement and analysis time using the described 3D system can be reduced to less than two minutes for each cast, whereas it may take more than six minutes to record measurements by the direct method. A limitation of the 3D system was that a dental cast still had to be constructed, however, the validity and reliability and long-term cost savings may enable the 3D system to compete with other systems. Further studies comparing direct and 3D methods are indicated to determine the validity and reliability of measurements of various dental variables found in different types of malocclusion, such as the irregularity index and curve of Spee.

Conclusion

The present study determined that most 3D dimensions could be measured with a high degree of validity and reliability, with less than 0.5 mm mean difference between direct and indirect measurements. The mean differences for measurements of mesiodistal crown widths were slightly greater than those for dental arch dimensions, but neither was regarded as clinically significant. The results of the present study support the view that plaster dental casts could be replaced by the use of 3D images from which tooth size and dental arch dimensions could be obtained for clinical diagnosis and treatment planning. In addition, the accuracy of a 3D imaging system measurement would enable dental cast analysis for research purposes. The described 3D system provides images at low cost, with easy storage, good preservation, and fast communication which are all beneficial features for medico-legal reporting.

Acknowledgment

The authors wish to thank the Universiti Sains Malaysia for funding this work through Grant No. 304/PPSG/6139046. Our sincere thanks to Dr Zulkepli Majid from the Geomatic Engineering Department, Faculty of Geoinformation Science and Engineering, Universiti Teknologi Malaysia for his unlimited support. We also wish to thank Mr Yusdirman Ahmad Yusuf from the Information System Unit at the Hospital of the Universiti Sains Malaysia.

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