European Journal of Orthodontics 29 (2007) 517–522
doi:10.1093/ejo/cjm044

Three-dimensional imaging of orthodontic models: a pilot study

Jennifer Asquith*, Toby Gillgrass* and Peter Mossey**
*Edinburgh Postgraduate Dental Institute and and **University of Dundee Dental Hospital and School, Scotland, UK

SUMMARY Computer-based digital orthodontic models have been developed that have the potential to replace dental casts. The aim of this study was to examine the accuracy and reproducibility of measurements made on digital models. Ten sets of orthodontic study models were scanned using the Arius3D Foundation System and three-dimensional (3D) images were produced by computer software. Two examiners individually measured 11 parameters on the conventional casts and the digital models on two occasions. The parameters included mesio-distal crown diameter, intercanine and intermolar width, arch length, overjet, and incisor crown height. The measurement techniques were compared using paired *t*-tests, the coefficient of reliability, and by calculating mean values and the difference between methods.

When comparing measurements made on digital models with those on dental casts, systematic errors were detected for five of the 11 parameters at the 10 per cent level. Random errors were a cause of concern for measurements of three parameters. The most accurate and reproducible measurements were lower intercanine width (mean difference between measurements 0.05 ± 0.32 mm) and overjet (mean difference 0.07 ± 0.33 mm). Most parameters on the digital models can be reliably measured, and digital models can potentially eliminate the requirement for the production and storage of dental casts, but this will depend on cost.

Introduction

Orthodontic study models are usually collected by clinicians to aid diagnosis, monitor treatment, and complement the written record. Study models are also used in research, audit, and teaching. The medico-legal requirement in the United Kingdom is that all clinical records, including study models, should be retained for a period of 11 years, or 11 years after a child patient reaches the age of 18 years (Machen, 1991). The need to retain dental casts for future reference has created storage problems for orthodontists (McGuinness and Stephens, 1992). A more convenient and cost-effective means of recording and maintaining this information accurately is needed.

Dental casts have been reproduced in two-dimensions by taking photocopies (Champagne, 1992) and photographs (Nollet *et al.*, 2004) of the casts. Three-dimensional (3D) reproduction of study models has been achieved using holography (Schwaninger *et al.*, 1977; Keating *et al.*, 1984; Buschang *et al.*, 1990) and stereophotogrammetry (Ayoub *et al.*, 1997; Bell *et al.*, 2003). The company who assisted in the study of Bell *et al.* (2003) felt unable to produce models of sufficient quality using stereophotogrammetry, and so it is not used commercially for his purpose. The shortcomings that have been identified with stereophotogrammetry and holography mean that conventional casts have still not been replaced.

Computer-based record keeping is routine in many orthodontic clinics. Digital photography and digital radiography, as well as computer-based charts and patient management systems, constitute an electronic patient record. Computer-based digital orthodontic models have been developed and have the potential to replace dental casts (Alcaniz *et al.*, 1999; Lu *et al.*, 2000; Hirogaki *et al.*, 2001; Santoro *et al.*, 2003; Quimby *et al.*, 2004). OrthoCAD introduced a digital model service to orthodontists in 1999. Data indicate that 10 per cent of orthodontists in Canada and the USA use digital models (Joffe, 2004).

The Arius3D Foundation System Scan (Inition, London, UK, http://www.inition.co.uk) captures colour and geometry simultaneously to produce digital representations of real objects. Scanned data are recorded and processed by the Arius3D Pointstream software: www.inition.co.uk/inition/product.php?URL_=product_digiscan_arius3d_pointstream) to transform the data into 3D colour images. The Arius3D system consists of a laser scanner and a motion control system for moving the camera. The laser scanning mechanism operates by using a class IIIb laser with combined red (R), green (G), and blue (B) light, and each point of the scanned object is characterized according to its location in space and colour. Each point on the object is described by six numerical values, these being positional values *X*, *Y*, and *Z*, and surface colour values R, G, and B.

Tooth size, arch form, and tooth–arch discrepancies can be assessed using study models. Calliper measurements are regarded as the ‘gold standard’, against which other measurement techniques are compared. The objective of this study was to compare measurements made on dental casts using callipers with those on digital models produced by the Arius3D system using the tools on Pointstream image suite, a Windows application.

Materials and methods

Study models

The sample comprised 10 sets of study models of Class I, II, and III malocclusions selected from the archives of the Department of Orthodontics, Edinburgh Postgraduate Dental Institute. The study models were all of good quality and accurately and uniformly trimmed with their base parallel to the occlusal surface. The models were chosen to provide a selection of malocclusions. All models had a full complement of permanent incisors, canines, first premolars, and first molars. All teeth had normal morphology with no teeth in the casts displaying visible attrition, caries or restorations affecting the mesio-distal crown diameter.

Reference marks

Reference marks were made on the study models using a 0.3 mm fine liner black pen. The points were marked on the mesio-buccal cusp tips of the first molars and on the mesial aspect of the incisal edge of the most prominent central incisor.

Scanning the study models

The study models were placed in occlusion on the granite table of the co-ordinate measuring machine (CMM), a device for dimensional measuring, with the heels placed on a reference plane at a known and fixed position (Figure 1). The Arius3D scanner moved across the models along the *x*-axis with the field of view of the scanner perpendicular to the CMM. The scanner was rotated to plus or minus 30 degrees on the spindle and the models were rescanned, thus producing three scans at a known position on the CMM. The maxillary and mandibular models were then scanned individually with the heels on the reference plane. The individual models were rescanned with both the scanner and models at various angles to ensure full capture of the study model geometry with no blind areas. The data produced by the scanner were converted to point cloud data on a personal computer and aligned to the original. Cleaning and alignment of the scanned point cloud data to produce the virtual models was supported using the Pointstream software.

Measuring the models

Two examiners (JA and TG) measured the dental casts and the 3D digital models independently. The same examiners repeated the measurements no sooner than one month later, under similar conditions. The examiners were given an instruction sheet and forms on which to record all measurements.

Measurements were obtained on the dental casts with a Mitutoyo digital calliper (Lawson-HIS, www.lawson-his.co.uk) equipped with a Vernier scale accurate to 0.01 mm. The mesio-distal widths of the teeth were measured as the greatest mesio-distal diameter from the mesial contact point to the distal contact point of each tooth, parallel to the occlusal plane. Incisor crown heights were measured from the incisal edge to the gingival margin down the long axis of the tooth. Intercanine width was measured from crown tip to crown tip and intermolar width from the mesio-lingual cusp tip of the first permanent molar to the mesio-lingual cusp tip of the contralateral tooth.

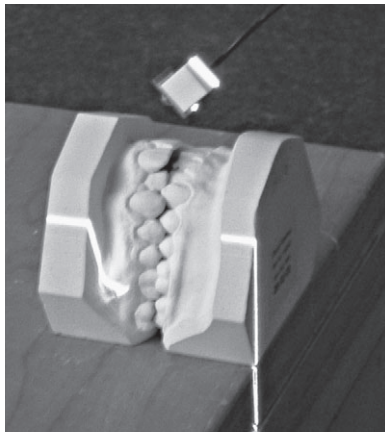

Figure 1 A set of orthodontic models being scanned using the Arius3D Foundation System laser scanner.

A metal ruler, accurate to 0.5 mm, was used to measure overjet from the middle of the incisal edge of the most prominent upper central incisor to the labial surface of the corresponding lower incisor, parallel to the occlusal plane. Arch length was measured as the perpendicular distance from the contact point between the two central incisors and a line connecting the distal surfaces of the primary second molars, or the second premolars, as described by Moorees (1959). A metal ruler was used to connect the distal surfaces of the primary second molars or second premolars.

The digital models were imported to a personal computer and the images were viewed using the Pointstream 3D image suite viewer. The digital models could be viewed in occlusion or individually (Figure 2) and could be rotated and magnified to facilitate point identification. A virtual tape measure was used to make measurements from point to point, and was accurate to 0.001 mm. In this study, however, all measurements made on digital models were recorded to the nearest 0.01 mm.

Mesio-distal tooth widths were measured using the tape measure tool on the Pointstream viewer by clicking on a point using the computer mouse, and dragging the line to the next point. The greatest distance between the mesial and distal contact points of each tooth was measured from the occlusal view. Incisor crown height was measured from the incisal edge to the gingival margin down the long axis of the clinical crown using the frontal view of the models, and overjet from the middle of the incisal edge of the most

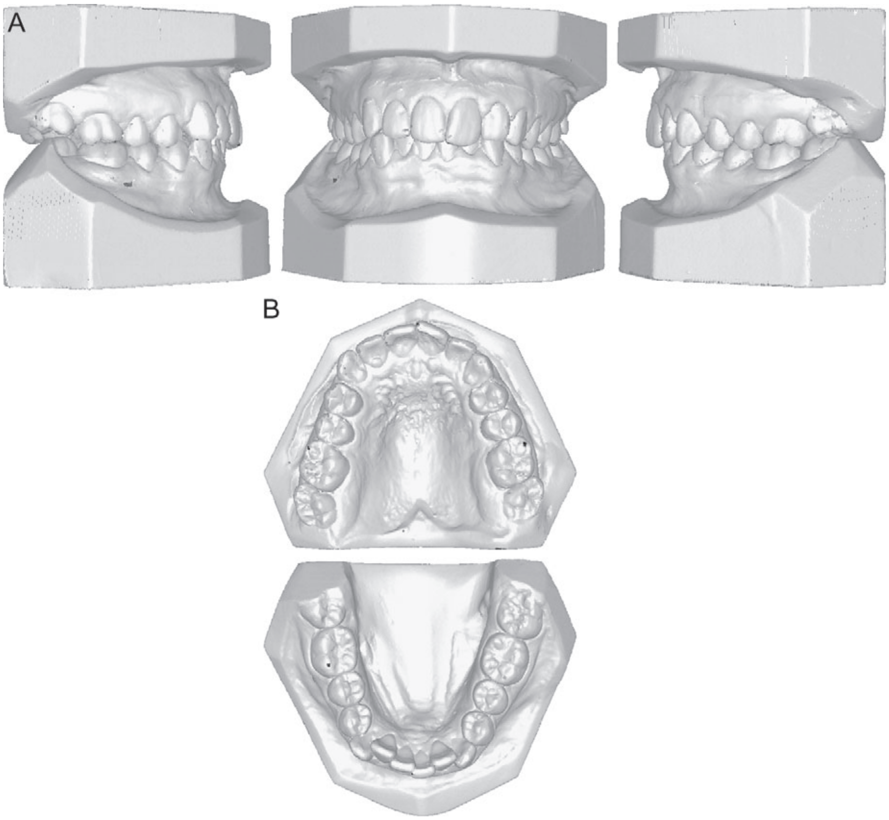

Figure 2 Five images of a single set of orthodontic models produced by the Arius3D Foundation System.

prominent upper central incisor to the labial surface of the corresponding lower incisor, using either the right or the left view of the models in occlusion.

Intercanine and intermolar widths were measured from crown tip to crown tip using the occlusal view of the individual models. Measurements were also made between reference points using the occlusal view. Arch length was measured by constructing a line to connect the primary second molars or second premolars by clicking on a point and dragging the tape measure and then constructing a line from the midpoint of the first line and dragging the tape measure to the contact point between the central incisors.

Data analysis and statistical tests

For each method of measurement, 11 parameters were selected for statistical analysis. The parameters were chosen to give a representative sample of measurements in three planes of space in order to test measurement accuracy in three dimensions. The following parameters were selected:

1. Upper right central incisor mesio-distal tooth width
2. Lower left first premolar mesio-distal tooth width
3. Upper left first molar mesio-distal tooth width
4. Upper right central incisor crown height
5. Lower left central incisor crown height
6. Lower intercanine width
7. Upper intermolar width
8. Upper arch length
9. Overjet
10. The distance between reference marks on the upper left first molar and most prominent upper central incisor
11. The distance between reference marks on the lower right first molar and most prominent lower central incisor

Systematic errors were detected by conducting a paired *t*-test for each pair of replicates. Houston (1983) suggested that *P* values smaller than 0.1 (i.e. differences at the 10 per cent level) indicated a statistically significant difference between the means. Random errors were estimated using the coefficient of reliability (Houston, 1983) and a comparison of measurement techniques was performed as described by Bland and Altman (1986). Intra- and interexaminer measurements were evaluated in an error study. When comparing measurements made on digital models with those made on dental casts, data from examiner 1 were used.

Results

Table 1 shows the difference between the means of the measurements of examiners 1 and 2 on two occasions. For

Table 1 Comparison between mean measurements made on 10 sets of study models by examiners 1 and 2. The values represent the difference in millimetres between the means of measurements obtained by the same examiner on two occasions ($n = 10$).

Parameter	Examiner 1		Examiner 2	
	Cast	Digital	Cast	Digital
UR1 mesio-distal width	0.11	0.27	0.02	−0.02
LL4 mesio-distal width	−0.01	0.15	−0.01	0.01
UL6 mesio-distal width	0.01	0.11	0.27	0.03
UR1 crown length	0.12	0.08	−0.08	−0.15
LL1 crown length	0.12	−0.11	0.08	−0.02
Lower intercanine width	0.09	−0.02	0.16	−0.49
Upper intermolar width	−0.06	−0.59	−0.44	−0.06
Upper arch length	0.11	−1.40	0.19	0.17
Overjet	−0.50	−0.37	−0.15	0.22
Reference UL*	−0.05	0.32	0.11	−0.31
Reference LR*	−0.04	0.14	0.08	0.29

*Reference, the distance between reference marks on the first molar and most prominent central incisor in the upper left quadrant or lower right quadrant.

examiner 1, the difference between the mean measurements on the dental casts fell within a range of −0.50 to +0.12 mm and on the digital models within a range −1.40 to +0.32 mm. The differences between the means of measurements of examiner 2 were within a range of −0.44 to +0.27 mm and −0.49 to +0.29 mm, respectively.

Intermethod agreement was assessed using the means of the measurements made on the dental casts and digital models on two occasions by examiner 1 (Table 2). Systematic errors were found for upper arch length, upper intermolar width, and the distance between reference marks on the lower right molar and central incisor, upper left first molar mesio-distal width and upper right central incisor mesio-distal width ($P < 0.1$; Houston, 1983). The level of random errors was sufficiently high to cause concern for the measurements of lower left first premolar mesio-distal width, lower left central incisor crown height, and upper arch length. Ten per cent of values for these parameters fell outside the mean difference ±2 standard deviation (SD). The coefficient of reliability for the lower premolar measurement was 0.402, for upper arch length 0.585, and for lower incisor crown height 0.796. A coefficient of reliability greater than 0.8 is generally accepted as high. The mean difference in measurements of upper arch length for the 10 study models was −4.78 mm, and 90 per cent of values were within 2 SD of this mean, lying between −9.74 and +0.18 mm. There was thus a high random as well as a systematic error for the measurement of upper arch length.

A systematic error was detected when examiner 1 measured the distance between the reference marks on the lower right molar and most prominent lower central incisor on the digital models, with a mean difference between the two occasions of 0.14 mm, which would be clinically insignificant (Table 1). A systematic error was also detected for this parameter when comparing the mean difference between methods (mean difference 0.39 mm), and this too would be clinically insignificant. The coefficient of reliability for measurements made using reference marks was greater than 0.97, and the differences in measurements between reference marks on plaster and computerized models were between ±2 SD of the mean difference (Table 2). Thus, systematic errors were detected, but were clinically insignificant, and the level of random errors was not sufficiently high to cause concern for measurements between reference marks.

Discussion

Sample size

Due to the high cost of scanning models in-house at the University of Dundee using the Arius3D system (£200 per set of models) and a limited budget, only 10 sets of models were scanned. This was considered adequate for carrying out a pilot study and would enable determination of the 'size effect' for a subsequent power calculation if a definitive study were to be required. The cost is related to the time taken to scan the models; the average time taken to scan a single set of models was approximately 3 hours, with time also taken for cleaning and alignment of the point cloud data.

Selection of study models

The study models selected for this study comprised Class I, Class II, and Class III malocclusions. They were chosen to represent the variety of patients who could be encountered in orthodontic practice. Eight of the 10 cases demonstrated mild to moderate crowding, one had spacing and one case, a Class I occlusion with well-aligned arches. Zilberman *et al.* (2003) constructed 20 set-ups using artificial teeth, simulating a variety of malocclusions in a study to evaluate the validity of measurements using virtual orthodontic models.

Marking points

Identification of points is a source of error. For this reason, dots were placed on a selection of landmarks in black pen on the study models. These points were used to eliminate landmark identification error in the measurements of reference distances.

Measuring dental casts and digital models

During the measurement of dental casts, the sharpened points of the callipers caused wear of the casts and this may have affected measurements of mesio-distal tooth width over repeated measurements.

Table 2 Intermethod agreement showing the standard deviations (SDs) of the means and coefficient of reliability (CR) of measurements made by examiner 1 on casts and digital models on two occasions ($n = 10$).

Parameter	Measurement (mm) Cast		Measurement (mm) Digital		Mean difference between methods	SD	*P* value	CR (%)	% of values ± 2 SD*
	Mean	SD	Mean	SD					
UR1 mesio-distal	8.77	0.42	8.62	0.53	0.16	0.24	0.07	0.901	0
LL4 mesio-distal	6.99	0.19	7.18	0.36	−0.19	0.33	0.10	0.402	10
UL6 mesio-distal	10.11	0.37	10.50	0.45	−0.38	0.25	<0.01	0.830	0
UR1 crown length	10.07	0.41	9.97	0.46	0.10	0.20	0.14	0.906	0
LL1 crown length	8.42	0.62	8.53	0.64	−0.11	0.40	0.39	0.796	10
Intercanine width	26.83	4.05	26.87	3.98	−0.05	0.32	0.65	0.997	0
Intermolar width	39.11	3.80	39.73	3.91	−0.62	0.38	<0.01	0.996	0
Arch length	28.58	2.09	33.36	3.03	−4.78	2.48	<0.01	0.585	10
Overjet	3.85	5.02	3.92	4.86	−0.07	0.33	0.53	0.998	0
Reference UL	39.82	2.54	40.18	2.81	−0.37	0.70	0.13	0.971	0
Reference LR	33.36	3.10	33.75	2.83	−0.39	0.39	0.01	0.996	0

P value represents the significance of the paired *t*-test; m.d., mesio-distal width.
*Comparison to show differences in measurements made on cast and digital models. The value refers to the percentage of measurements lying above or below 2 SD of the mean difference.

The images of 3D digital models are viewed in two-dimensions on the computer screen and so the identification of points and planes is difficult.

Measurement accuracy and reproducibility

Landmarks can be difficult to identify and the examiner's opinion concerning the exact location of a point can vary at random. This error may be reduced by precise definition of points and each examiner in this study was provided with an instruction sheet describing the points to be measured. Random errors are also reduced if measurements are replicated and averaged, however measurements were taken on only two occasions in this study and the sample size was small.

The reliability of the different parameters varied, with some more reliable than others. The measurements of overjet and intercanine width were most accurate and reproducible, whereas those for upper arch length and lower premolar mesio-distal width were found to be least accurate and reproducible. When measuring arch length using a constructed point, the values obtained from the digital models were larger than those for the dental casts. This systematic overestimate of arch length was most likely due to the measurement tool on the Pointstream image suite viewer measuring this distance in three planes of space, such that the depth of the palatal vault was incorporated in this constructed measurement.

The mean difference between the two methods in the measurement of lower premolar mesio-distal tooth width may be attributed to crowding in this region on many of the casts making identification of points difficult, particularly on digital models. The mean differences between measurements of mesio-distal tooth width made on a selection of teeth by the different methods were within a small range (0.16–0.38 mm). This is in agreement with the findings of Santoro *et al.* (2003) when they compared measurements of individual tooth widths made on dental casts with those on digital models.

Statistical significance versus clinical significance

Systematic errors of more than 0.5 mm for single tooth measurements and overjet, or greater than 5 per cent of the distance for measurements of arch breadth, arch length, and distances between reference marks, were regarded as clinically unacceptable for the purposes of this study. The mean difference between methods in the measurement of upper arch length was clinically unacceptable as it was greater than 5 per cent of the mean distance. If arch length had been measured in an alternative way, such as the sum of the right and left distances from the mesial anatomic contact points of the first permanent molars to the contact point of the central incisors (Little *et al.*, 1990), the difference between methods may not have been clinically significant as there would be no constructed point. The mean difference between methods for the remaining 10 parameters may be regarded as clinically insignificant. Despite the small sample size, this pilot study shows that measurements made on digital models are clinically accurate.

Suggestions for future research

3D technology could be used as follows and would build on the findings of the present study:

1. To scan dental impressions directly in order to produce digital models. Measurements made on these digital models could be compared with measurements made on dental casts.

2. 3D point cloud data captured during laser scanning of either impressions or models can be transferred to a standard computer-aided design system which is able to produce a scale model using modern replication technologies, such as rapid prototyping reverse engineering. The accuracy and measurement reproducibility of models produced in this way should be assessed.
3. The feasibility of applying occlusal indices such as the Index of Orthodontic Treatment Need, the Index of Complexity Outcome and Need and the Peer Assessment Rating index to digital models could be tested. Also quantitative outcome measurements for cleft lip/palate models such as the modified Huddart/Bodenham system (Mossey *et al.*, 2003) could be made on scanned digital models and compared with those made on original dental casts.

Conclusions

3D digital study models may be produced by laser scanning using the Arius3D Foundation System.

Most parameters on digital models can be reliably measured, with a mean difference between measurements made using the two methods of less than 0.5 mm. The mean difference between methods for the measurement of upper intermolar width was slightly greater at 0.62 mm, but would not be regarded as clinically significant.

Upper arch length is not reliably reproduced, but this was due to the inability of the measurement software to produce a constructed point for this parameter.

3D digital models can potentially eliminate the requirement for the production and storage of conventional dental casts, and in recent times the cost limitation of laser linear scanning has been addressed by high throughput commercial production.

Address for correspondence

Professor Peter Mossey
University of Dundee Dental Hospital and School
1 Park Place
Dundee DD1 4HR
UK
E-mail: p.a.mossey@dundee.ac.uk

Acknowledgement

This study was supported by the Edinburgh Postgraduate Dental Institute. The study models were scanned by Kestrel 3D Group at the University of Dundee who use the Arius3D scanner. The authors wish to thank Professor David Stirrups for statistical advice and Rosemary Inglis for providing secretarial assistance.

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