SCIENTIFIC SECTION

A comparison of plaster, digital and reconstructed study model accuracy

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Objectives: To evaluate the accuracy and reproducibility of a three-dimensional (3D) optical laser-scanning device to record the surface detail of plaster study models. To determine the accuracy of physical model replicas constructed from the 3D digital files.

Design and setting: A method comparison study using 30 dental study models held in the Orthodontic Department, School of Dentistry, Cardiff University.

Materials and methods: Each model was captured three-dimensionally, using a commercially available Minolta VIVID 900 non-contact 3D surface laser scanner (Konica Minolta Inc., Tokyo, Japan), a rotary stage and Easy3DScan integrating software (TowerGraphics, Lucca, Italy). Linear measurements were recorded between landmarks, directly on each of the plaster models and indirectly on the 3D digital surface models, on two separate occasions by a single examiner. Physical replicas of two digital models were also reconstructed from their scanned data files, using a rapid prototyping (RP) manufacturing process, and directly evaluated for dimensional accuracy.

Results: The mean difference between measurements made directly on the plaster models and those made on the 3D digital surface models was 0.14 mm, and was not statistically significant ($P=0.237$). The mean difference between measurements made on both the plaster and virtual models and those on the RP models, in the z plane was highly statistically significant ($P<0.001$).

Conclusions: The Minolta VIVID 900 digitizer is a reliable device for capturing the surface detail of plaster study models three-dimensionally in a digital format but physical models of appropriate detail and accuracy cannot be reproduced from scanned data using the RP technique described.

Key words: Orthodontics, study models, three-dimensional imaging

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Introduction

Orthodontic treatment outcome and treatment change have traditionally been recorded with gypsum-based study models, which are heavy and bulky, pose storage and retrieval problems, are liable to damage and can be difficult and time consuming to measure.[1–5] Legislation relating to the retention of patient records after the completion of treatment[6] has led to huge demands on space for storage that has prompted the development of alternative methods of recording occlusal relationships (Table 1) and electronic storage of records.[7–13]

The replacement of plaster study models with virtual images has several advantages including ease of access, storage and transfer,[14] and the accuracy of image capture techniques has been reported.[1,3,15–20] However, if the physical restoration of a digital occlusal record is needed, possibly for medico–legal reasons, an accurate method of three-dimensional (3D) reconstruction is required.

Rapid prototyping (RP) systems, such as stereolithography, generate 3D models from a digital file through incremental layering of photo-curable polymers.[21] The dimensional accuracy of physical replicas reproduced using the stereolithography technique has been evaluated

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by a number of authors. Barker *et al.*[22] found a mean difference of 0.85 mm between measurements made on actual dry bone skulls and physical replicas of the skulls produced by stereolithography from three-dimensional computed tomography (3D-CT) scans of the original dry bone skulls. They concluded that RP models could be confidently used as accurate 3D replicas of complex anatomic structures. Using similar techniques, Kragskov *et al.*[23] and Bill *et al.*[24] found mean differences of −0.3 to 0.8 mm and ±0.5 mm between measurements on 3D-CT images and stereolithographic models.

The objectives of this study were:

- to assess the reproducibility of a conventional method of using a hand-held vernier calliper to measure plaster study models;
- to develop an efficient and reproducible method of capturing a 3D study model image, in a digital format, using the Minolta VIVID 900 non-contact surface laser-scanning device (Konica Minolta Inc., Tokyo, Japan);
- to assess the reproducibility of measurements made on the on-screen 3D digital surface models captured using the scanning system set-up developed;
- to compare the accuracy of measurements made on the 3D digital surface models and plaster models of the same dentitions;

Table 1 Alternative methods of recording occlusal relationships.

Two-dimensional techniques	
Conventional photography	Cookson (1970)
	Burstone (1979)
	Dervin *et al.* (1976)
	McKeown *et al.* (2002)
Photocopying	Singh and Savara (1964)
	Huddart *et al.* (1971)
	Mazaheri *et al.* (1971)
	Champagne (1992)
	Schirmer and Wiltshire (1997)
	McCance *et al.* (1991)
	Yen (1991)
Flatbed scanner	Tran *et al.* (2003)
Three-dimensional techniques	
Optocom	Van der Linden *et al.* (1972)
Reflex plotters	Suzuki (1980)
	Foong *et al.* (1999)
Reflex metrograph	Scott (1981, 1984)
	Takada *et al.* (1983)
	Speculand *et al.* (1988b)
Reflex microscope	Scott (1981)
	Speculand *et al.* (1988a, b)
	Johal and Battagel (1997)
Travelling microscope	Bhatia and Harrison (1987)
Moiré topography	Takasaki (1970)
	Kanazawa *et al.* (1984)
	Mayhall *et al.* (1997)
Stereophotogrammetry	Halazonetis (2001)
	Jones (1979)
	Jones and Richmond (1984)
	Ayoub *et al.* (1997)
	Bell *et al.* (2003)
Telecentric lens photography	Kennedy (1979)
Holography	Schwanginger *et al.* (1977)
	Burstone *et al.* (1978)
	Ryden *et al.* (1982)
	Keating *et al.* (1984)
	Harradine *et al.* (1990)
	Buschang *et al.* (1990)
	Martesson and Ryden (1992)
	Romeo (1995)
Optical profilometer	Berkowitz (1982)
Image analysis system	Brook *et al.* (1983)
	Brook *et al.* (1986)
Three-dimensional computerised tomography (3D-CT)	Quintero (1999)
	Mah and Baumann (2001)
	Darvann *et al.* (2001)
	Kuo and Miller (2003)

Table 1 Continued.

Two-dimensional techniques	
Structured light scanning methods	Harada *et al.* (1985)
	Yamamoto *et al.* (1988)
	Laurendeau *et al.* (1991)
	Wakabayashi *et al.* (1997)
	Hirogaki *et al.* (1998, 2001)
	Kojima *et al.* (1999, 2003)
	Sohmura *et al.* (2000)
	Nagao *et al.* (2001)
	Hayashi *et al.* (2000)
	Foong *et al.* (1999)
	Lu *et al.* in (2000)
	Alcaniz *et al.* (1998, 1999)
	Brosky *et al.* (2002, 2003)
	Delong *et al.* (2002, 2003)
	Schelb *et al.* (1985)
	Braumann *et al.* (1999)
Intra-oral scanning devices	Delong *et al.* (2003)
	Commer at al. (2000)
Commercially available 3D digital study models	Zilberman *et al.* (2003)
	Redmond (2001)
	Tomassetti *et al.* (2001)
	Santoro *et al.* (2003)
	Baumrind (2001)
	Kuo and Miller (2003)
	Freshwater and Mah (2003)
	Hans *et al.* (2001)
	Baumrind *et al.* (2003)
	Mah and Sachdeva (2001)

- to evaluate the feasibility of fabricating accurate 3D hard copies of dental models from the laser scan data, by an RP process (stereolithography).

Null hypotheses

- There is no difference in the dimensional accuracy of 3D digital surface models, captured with the surface laser-scanning technique described, and plaster study models.
- There is no difference in the dimensional accuracy of physical model replicas, fabricated from the laser scan data by RP, and plaster study models.

Materials and methods

Manual measurements

The local REC chairman confirmed that no ethical approval was required for this study. A minimum of 7–10 models per group were calculated to be required to allow a 90% chance of detecting a 0.3 mm difference in related sample means (SD=0.2) at the 5% level of significance (alpha=0.05, power=0.90).[25] Thirty randomly selected plaster study models, held in the Orthodontic Unit of University Dental Hospital, Cardiff, were used in the study. Each study model was cast in matt white Crystal R plaster (South Western Industrial Plasters, Chippenham, UK) and conventionally trimmed.[26] To be included in the study the plaster study models had to completely reproduce the arch, show no surface marks, loss of tooth material, voids or fractures and demonstrate varying degrees of contact point and buccolingual tooth displacements.

A hand held digital calliper (series 500 Digimatic ABSolute Caliper, Mitutoyo Corporation, Kawasaki, Japan), was used to manually measure the plaster models. This calliper had a measurement resolution of 0.01 mm, was accurate to ±0.02 mm in the 0–200 mm range and automatically downloaded data eliminating measurement transfer and calculation errors.

All plaster models were measured in a bright room without magnification. The plaster models were not prepared in any way prior to measuring and the anatomical dental landmarks used in the measurements were not pre-marked. A single examiner conducted all the measurements after an initial training period.

Twenty linear dimensions were measured, on each model, in each of the three planes (x, y and z) with all measurements being recorded to the nearest 0.01 mm. The following dimensions were selected for measurement:

x plane:

1. intercanine distance – measured as the distance between:
   (i) the occlusal tips of the upper canines;
   (ii) the occlusal tips of the lower canines.
2. interpremolar distances – measured as the distance between:
   (i) the buccal cusp tips of the upper and lower first and second premolars;
   (ii) the palatal cusp tips of the upper first and second premolars;
   (iii) the lingual cusp tips of the lower first premolars;
   (iv) the mesiolingual cusp tips of the lower second premolars.
3. intermolar distances – measured as the distance between:
   (i) the mesiopalatal cusp tips of upper first and second molars;
   (ii) the mesiobuccal cusp tips of the upper and lower first and second molars;
   (iii) the mesiolingual cusp tips of lower first and second molars;
   (iv) the disto-buccal cusp tips of the upper and lower first molars.

y plane:

1. in the upper arch the distance from the mesiopalatal cusp tip of the upper second molar to:
   (i) the mesiopalatal cusp tip of the upper first molar;
   (ii) the palatal cusp tip of the upper first and second premolar;
   (iii) the cusp tip of the upper canine;
   (iv) the mesio-incisal corner of the upper lateral incisor.

These dimensions were measured on both sides of the upper arch.

2. in the lower arch the distance from the mesiolingual cusp tip of the lower second molar to:
   (i) the mesiolingual cusp tip of the lower first molar and second premolar;
   (ii) the lingual cusp tip of the lower first premolar;
   (iii) the cusp tip of the lower canine;
   (iv) the mesio-incisal corner of the lower lateral incisor.

These dimensions were measured on both sides of the lower arch.

z plane:

1. The clinical crown height of all the teeth, in both upper and lower arches, from the second premolar to second premolar inclusive, measured as the distance between the cusp tip and the maximum point of concavity of the gingival margin on the labial surface.

Measurements were made on two occasions separated by at least one week.

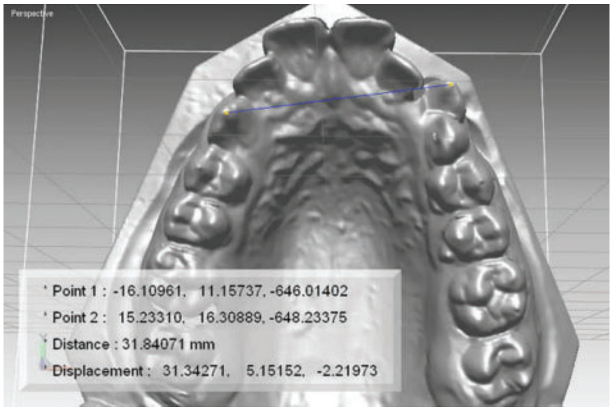

Figure 1 On-screen 3D virtual model image. Intercanine width measured

Virtual measurements

A non-contact laser-scanning device (Minolta VIVID 900) was used to record the surface detail of each of the 30 study models using a telescopic light-receiving lens (focal distance f=25 mm) and rotary stage (ISEL-RF1, Konica Minolta Inc., Tokyo, Japan). The rotary stage facilitated the acquisition of multiple range maps by moving the plaster study models in sequence by a controlled rotation as they were being scanned, thus ensuring the entire visible surface of each plaster model was captured. The stage was controlled by a computer software program (Easy3DScan Tower Graphics, Lucca, Italy) and integrated controller box (IT116G, Minolta Inc., Osaka, Japan).

Easy3DScan was used to align, merge and simplify the range maps acquired at different angles to produce a composite surface dataset that was then imported into the RapidForm 2004 software program (INUS Technology Inc., Seoul, Korea) as a triangulated 3D mesh (Figure 1). An automated measuring tool was used to record the same measurements that had been conducted manually on the plaster study models. The 3D digital surface models were magnified and rotated on screen to aid identification of the anatomical landmarks as necessary. Linear distances between landmarks were calculated automatically to five decimal places (Figure 1). Replicate measurements were made on all digital model images with a time interval of at least one week.

Measurement of reconstructed models

One pair of upper and lower plaster models were scanned individually using an identical protocol, adhering to the inclusion criteria listed previously. Only one set of models was evaluated due to the current cost of stereolithography. The scanned data for both upper and lower plaster models were saved as binary STL files and imported into the Magics RP software (Materialise Inc., Leuven, Belgium).

A 3D Systems stereolithography machine (SLA-250/40, 3D Systems Inc., Valencia, CA, USA) containing a hybrid epoxy-based resin (10110 Waterclear, DSM Somos, New Castle, DE, USA) was used to construct replica (RP) models from the digital files using a build layer thickness of 0.15 mm (Figures 2 and 3).

Identical measurements, in x, y and z planes, were made on the reconstructed stereolithography models to those recorded on the original plaster study models and virtual models. Replicate measurements were made one week later.

Statistical analysis

A Bland–Altman analysis[27] was undertaken to determine agreement between repeat model measurements. Intra-rater reliability was assessed by visually comparing the difference in repeat measurements and performing non-parametric, Wilcoxon signed rank hypothesis tests. This is described in the Results section.

Results

Data analysis demonstrated a non-normal distribution of results, and non-parametric tests (Wilcoxon signed rank test) were therefore employed in the statistical analysis.

No significant difference ($P>0.2$) was demonstrated in measurements at initial time (T1) and one week later (T2) for the manual measurement of plaster study models (Table 2, Figure 4), 3D digital surface model measurement (Table 3, Figure 5) or manual measurement of the stereolithography, reconstructed models (Table 4, Figure 6). Almost all points were clustered around the mean difference of zero, within two standard deviations of the mean difference (Figures 4–6) indicating good intra-rater reliability.

A comparison of linear measurements made on the plaster study models and 3D digital surface (virtual) models is presented in Table 5 and Figure 7. The mean difference in all planes was 0.14 mm (SD=0.10 mm) and was not statistically significant ($P>0.2$).

Measurements made in x and y planes were not significantly different for reconstructed models and plaster models ($P>0.3$) or 3D digital surface models ($P>0.5$). However, in the z plane, measurement differences were significantly different ($P<0.001$, Tables 6 and 7; Figures 8 and 9). All z plane reconstructed model measurements were significantly smaller than the corresponding plaster and 3D digital surface model measurements.

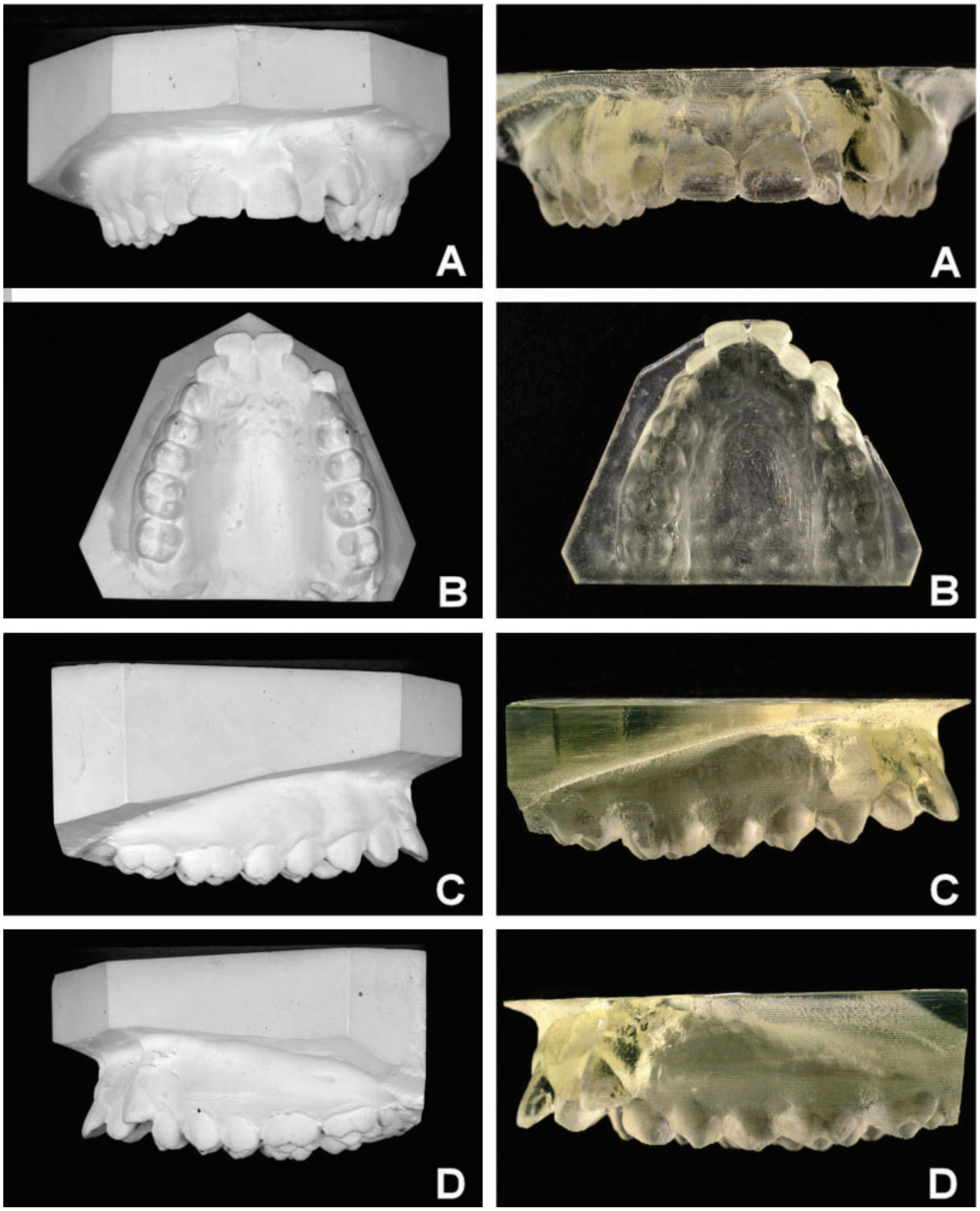

Figure 2 Original upper plaster model (left) and stereolithography model (right) as seen from (A) frontal, (B) occlusal, (C) right buccal and (D) left buccal directions

Discussion

This study has demonstrated a simple and reproducible method of study model measurement. The excellent reproducibility of plaster, digital and reconstructed model measurements reported compares favourably with Zilberman *et al.*[20] and Bell *et al.*[28] who reported mean intra-operator errors of 0.18 and 0.17 mm respectively, when the same points were measured by the same operator at different times on plaster study models, and Stevens *et al.*[14] who reported a concordance correlation coefficient of 0.88 for the measurement of digital models using *e*model software (GeoDigm, Chanhassen, MN, US). The reconstructed stereolithography model measurements in this study demonstrated a greater range in repeated absolute measurement differences (0.02–0.41 mm) compared to those for the other two methods (0.01–0.34 mm) reflecting the greater difficulty in measuring these models.

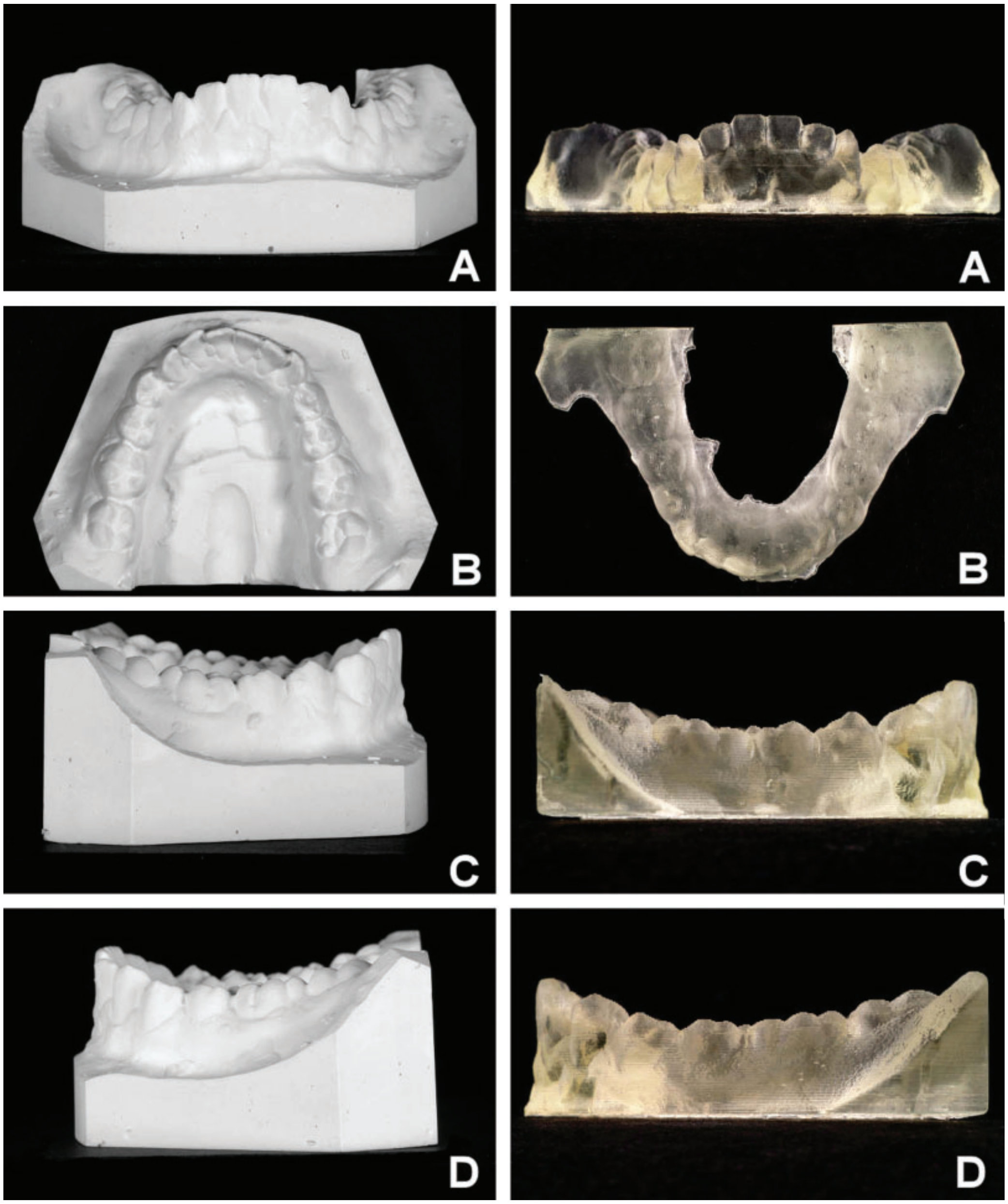

Figure 3 Original lower plaster model (left) and stereolithography model (right) as seen from (A) frontal, (B) occlusal, (C) right buccal and (D) left buccal directions

This study has also demonstrated the validity of digital (virtual) models derived from the laser scanning process described. The problems of trying to acquire dimensionally accurate images using structured light scanning methods have been reported by Bibb *et al.*[29] and Mah and Hatcher.[30] The light beam from structured light scanners travels in straight lines so any object surfaces that are obscured or are at too great an angle to the line of sight of the light source will not be scanned. This results in 'voids' or 'holes' in the scanned surface data. To overcome this problem the object or the scanner needs to be moved to different angulations and the scan process repeated at each angle. For irregular objects multiple scans of the same object from different angles may need to be acquired. The data from each of these scans can then be 'stitched' (registered and merged) together using special software programs to produce a single composite surface model of the object.[29,31,32] Compounding these difficulties are the errors introduced during computer processing of the acquired data that are necessary to reduce artefacts and yet retain detail, while errors can also be

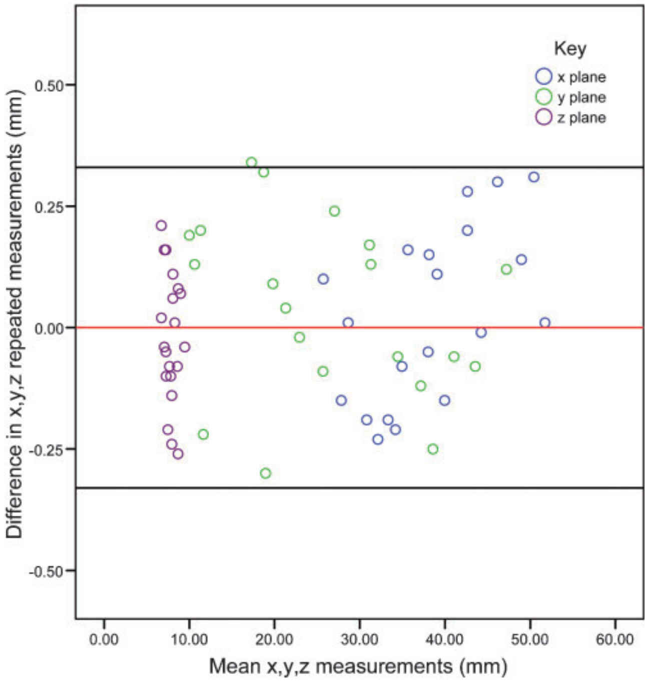

Figure 4 Bland Altman plot for repeat measurements plaster model. Twenty measurements in each plane repeated on 30 models (reference lines showing 2SD)

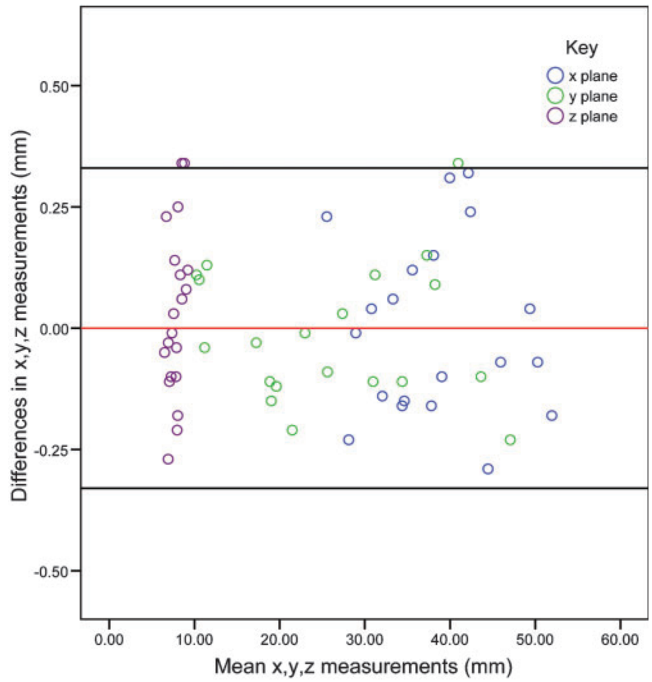

Figure 5 Bland Altman plot for repeat virtual model measurements. Twenty measurements in each plane repeated on 30 models (reference lines showing 2SD)

Table 2 Variation in repeat measurements of plaster models – 20 measurements in each plane repeated on 30 models.

Plane	N	Mean difference (mm)	Standard deviation (mm)	*P* value
x plane	20	0.15	0.09	0.601
y plane	20	0.16	0.09	0.313
z plane	20	0.11	0.07	0.489
x,y,z planes	60	0.14	0.09	0.558

Table 3 Variation in repeat measurements of virtual models – 20 measurements in each plane repeated on 30 models.

Plane	N	Mean difference (mm)	Standard deviation (mm)	*P* value
x plane	20	0.15	0.93	0.823
y plane	20	0.12	0.75	0.549
z plane	20	0.14	0.11	0.501
x,y,z planes	60	0.14	0.92	0.965

introduced during the merging together of the multiple perspectives to form the single composite surface model of the object being scanned.[30]

A number of authors who have evaluated alternative ways of measuring study models have suggested what they consider a clinically significant measurement difference. Schirmer and Wiltshire[33] regarded a measurement difference between alternative measurement methods of less than 0.20 mm as clinically acceptable. Hirogaki *et al.*[11] suggested the accuracy required with orthodontic study models to be about 0.30 mm while Halazonetis[32] reported that an accuracy of 0.50 mm was sufficient for head and face laser-scanning but would be inadequate for scanning study models. Bell *et al.*[28] investigating the accuracy of the stereo-photogrammetry technique for archiving study models decided a mean difference of 0.27 mm (SD=0.06 mm) between this technique and measurements made by hand on plaster models was unlikely to have a significant clinical impact.

The accuracy of the on-screen virtual models as reported in this study compares favourably with some

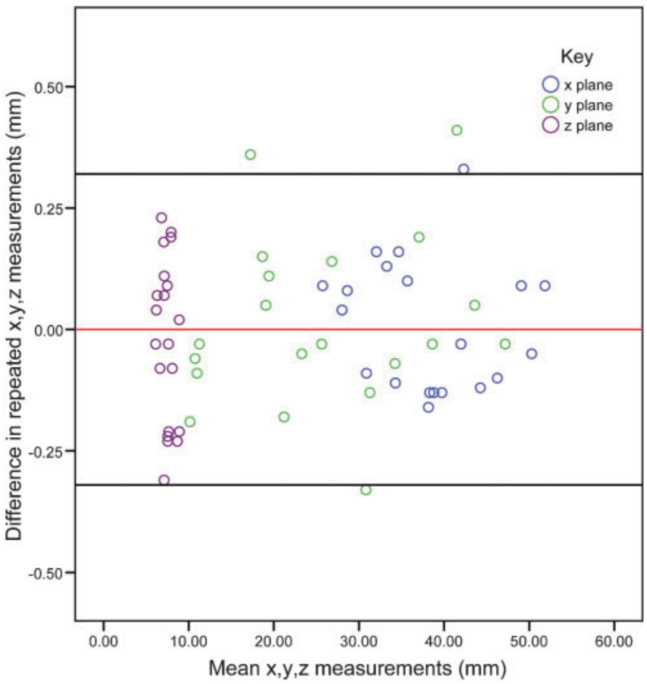

Figure 6 Bland Altman plot for repeat stereolithography model measurements. Twenty measurements in each plane repeated on one pair of models (reference lines showing 2SD).

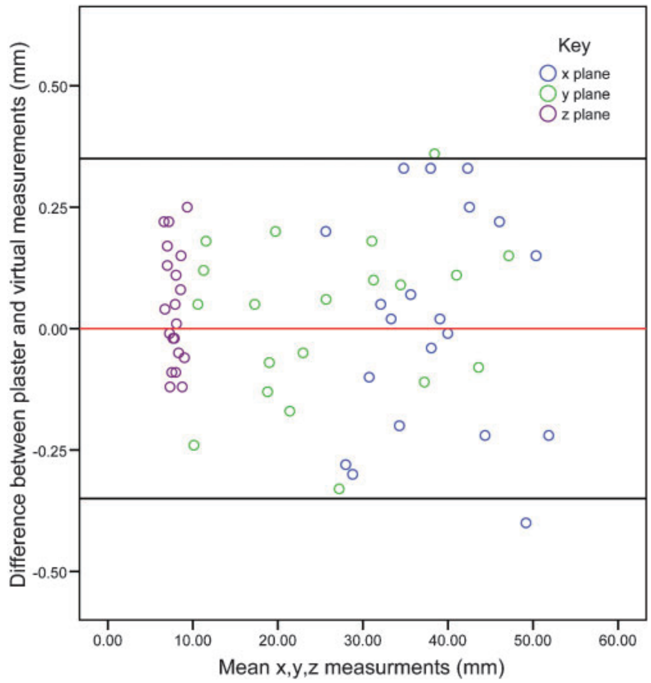

Figure 7 Bland Altman plot for differences in plaster and virtual model measurements (reference lines showing 2SD)

Table 4 Variation in repeat measurements of the reconstructed model – 20 measurements in each plane repeated on one model.

Plane	N	Mean difference (mm)	Standard deviation (mm)	*P* value
x plane	20	0.12	0.06	0.985
y plane	20	0.13	0.11	0.985
z plane	20	0.14	0.09	0.550
x,y,z planes	60	0.13	0.09	0.938

Table 5 Difference between plaster and virtual model measurements (means of 20 measurements in each plane compared).

Plane	N	Mean difference (mm)	Standard deviation (mm)	*P* value
x plane	20	0.19	0.12	0.765
y plane	20	0.14	0.09	0.501
z plane	20	0.10	0.07	0.218
x,y,z planes	60	0.14	0.10	0.237

studies but less favourably than with others. These studies varied greatly in their 3D capture techniques and software analysis systems (Table 8).

The statistically significant difference between measurements made directly on the plaster models and those made on the reconstructed models was largely due to errors in the *z* plane. The stereolithography models were built in 0.15 mm layers from a clear resin. Model translucency made landmark identification difficult and layering resulted in some loss of surface detail particularly at the cervical margin (Figures 2 and 3). In addition, errors in data conversion and data manipulation generated while converting digital surface models to stereolithography file format can result in some distortion[30,34] and the RP technique can also introduce errors due to model shrinkage during building and post-curing.[22] However, clinical significance of these errors will depend on the intended purpose of the reconstructed model. The models may not be sufficiently accurate for appliance construction but may be sufficient to demonstrate pre- or post-treatment occlusal relationships. Unfortunately, the current prohibitive

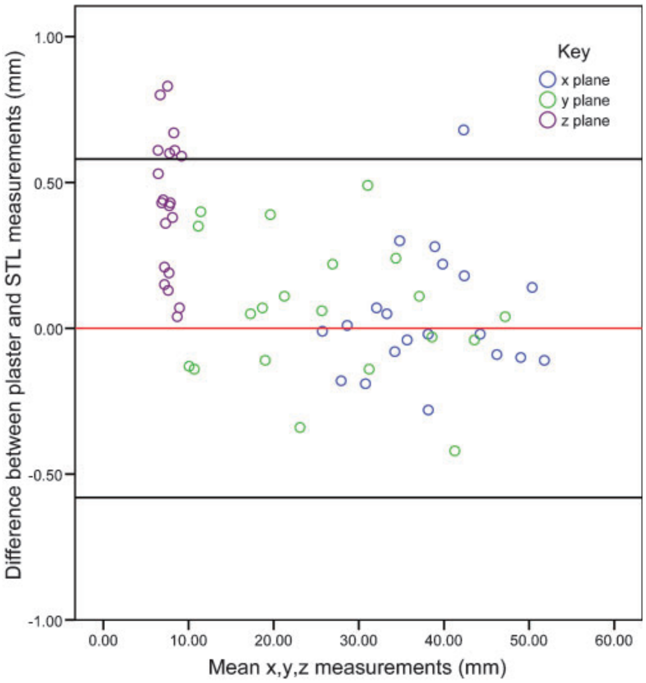

Figure 8 Bland Altman plot for differences in plaster and stereolithography model measurements (reference lines showing 2SD)

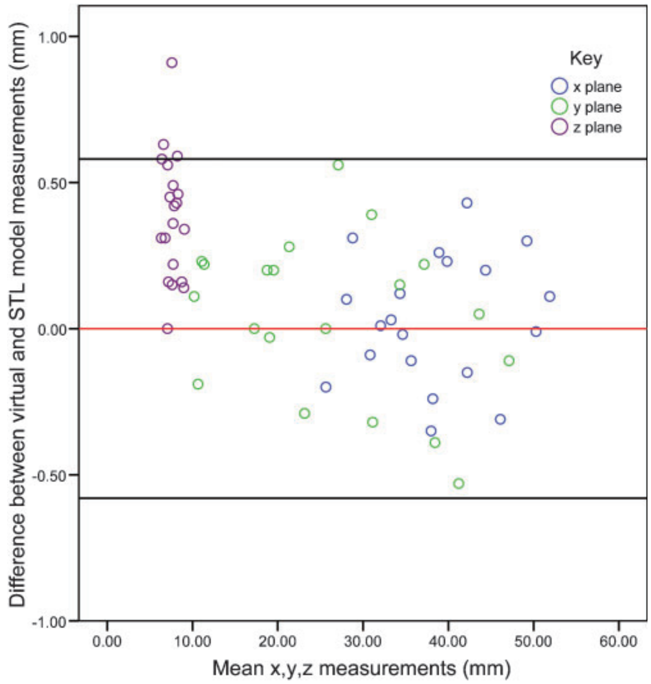

Figure 9 Bland Altman plot for differences in virtual and stereolithography model measurements (reference lines showing 2SD)

Table 6 Difference between plaster and reconstructed model measurements (means of 20 measurements in each plane compared).

Plane	N	Mean difference (mm)	Standard deviation (mm)	*P* value
x plane	20	0.15	0.16	0.645
y plane	20	0.19	0.15	0.360
z plane	20	0.42	0.23	>0.000**
x,y,z planes	60	0.26	0.22	>0.000**

Table 7 Difference between virtual and reconstructed model measurements (means of 20 measurements in each plane compared).

Plane	N	Mean difference (mm)	Standard deviation (mm)	*P* value
x plane	20	0.18	0.12	0.550
y plane	20	0.22	0.16	0.513
z plane	20	0.38	0.21	>0.000**
x,y,z planes	60	0.25	0.21	>0.000**

cost of stereolithography limited this study to the evaluation of only one pair of reconstructed models.

This study has presented a novel method of digitally recording study model data, offering the profession a valid alternative to the use of conventional plaster models and the potential to significantly reduce the burden of model storage. In addition, the potential for physical reconstruction of a model from the digital archive has been demonstrated which may go towards addressing medicolegal concerns.

Conclusions

- The use of using a hand held vernier calliper to measure plaster study models was reliable and reproducible.
- The Minolta VIVID 900 is a reliable device for capturing the surface detail of plaster study models three-dimensionally in a digital format using the protocol described.
- The measurement of the captured ‘on-screen’ 3D digital surface models was reproducible.

Table 8 Accuracy of various 3D capture techniques (Average measurement error is the mean difference between measurements made on virtual models and the original plaster models).

Author	Type	Device	Average measurement	Landmark/Identification
Wakabayashi *et al.* (1997)	Point laser	Mitsubishi, MD1211-40	<0.072 mm	Landmarks not identified
Kojima *et al.* (1999)	Line laser	Hitachi, HL6712G Laser	0.03 mm	Not specified
Motohashi and Kuroda (1999)	Line laser	UNISN, 3D VMS-250R	0.00–0.20 mm	Not specified
Lu *et al.* (2000)	Laser	Not indicated	<0.10 mm	Not specified
Commer *et al.* (2000)	Line laser	POS-PLD-50, Laser 2000	not more than + 0.20 mm	Landmarks identified by marking
Sohmura *et al.* (2000)	Line laser	Minolta VIVID700	0.08–0.35 mm	Landmarks not identified
Hirogaki *et al.* (2001)	Line laser	Cubesper Laser	<0.30 mm	Landmarks not identified
Tomassetti *et al.* (2001)	Destructive laser scanner	OrthoCAD	1.2 mm	Overall Bolton Discrepancy
Kusnoto and Evans (2002)	Line laser	Minolta VIVID700	x=0.20 mm, z=0.70 mm	Landmarks identified by marking
Santoro *et al.* (2003)	Destructive laser scanner	OrthoCAD	0.16–0.49 mm	Landmarks not identified
Bell *et al.* (2003)	Stereophotogrammetry	Not indicated	0.27 mm	Landmarks identified by marking
Quimby *et al.* (2004)	Destructive laser scanner	OrthoCAD	0.15–0.66 mm	Landmarks not identified

- The measurement of 3D digital surface models and plaster models of the same dentitions showed good agreement.
- The detail and accuracy of physical models, reconstructed from digital data, may not be sufficient for certain applications, using the standard stereolithography techniques described.
- Improved RP techniques may offer a more accurate method of model reconstruction from digital archives.

Future work

A stereolithography process employing thinner layers or other RP technologies that use significantly thinner build layers may address the deficiencies of the reconstructed models used in this study. Techniques that should be investigated include digital light processing based machines (EnvisionTEC GmbH, Gladbeck, Germany) and the various printing based processes such as poly-jet modelling (Objet Geometries Ltd, Rehovot, Israel), multi-jet modelling (3D Systems Inc. Rock Hill, SC, USA) and single head jetting (Solidscape Inc., Merrimack, NH, USA). These processes are all capable of producing physical models with a layer thickness of up to 10 times thinner than the stereolithography models described in this paper (layer thicknesses range from 0.013 to 0.150 mm).

Contributors

Andrew Keating, Richard Bibb and Jeremy Knox were responsible for study design. Richard Bibb contributed to this work while at the National Centre for Product Design and Development Research, University of Wales Institute Cardiff, which supplied the stereolithography models. Andrew Keating was responsible for data collection. Andrew Keating and Alexei Zhurov were responsible for data manipulation and processing. All authors were responsible for data analysis and preparation of manuscript. Jeremy Knox is the guarantor.

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