SCIENTIFIC SECTION

Assessment of the accuracy of a three-dimensional imaging system for archiving dental study models

A. Bell and A. F. Ayoub
Glasgow Dental Hospital and School, UK

P. Siebert
University of Glasgow, UK

Abstract

Objective: The use of stone and plaster study models is an integral part of any dental practice and is required for research. Storage of study models is problematic in terms of space and cost. Ayoub *et al.*[1] introduced a new technique based on the recent advances in stereophotogrammetry for archiving dental study models in a digital format. However, assessment of the accuracy of the generated three-dimensional (3D) models has not been carried out yet. It was the aim of this study to evaluate the accuracy of this technique.

Design: A comparative assessment between direct measurements of dental study models and measurements of computer generated 3D images of the same study models was performed.

Materials and methods: Twenty-two dental study models stored at Glasgow Dental Hospital and School for the purposes of research were used in the study. The models were captured in three dimensions using a photostereometric technique and stored in digital format.

Main Outcome Measures: Measurements were conducted directly on dental study models and on the computer generated 3D images using Euclidean Distance Matrix Analysis.[2] The difference between the two sets of measurements was statistically analysed using a two-sample *t*-test.

Results: The average difference between measurements of dental casts and 3D images was 0.27 mm. This difference was within the range of operator errors (0.10–0.48 mm) and was not statistically significant ($P < 0.05$).

Conclusion: This study shows that it is possible to use 3D imaging to store dental study models for treatment monitoring and research with a satisfactory degree of accuracy.

Index words: dental casts, dimensional accuracy, study models, 3-D imaging

Received 22 November 2002; accepted 2 March 2003

Introduction

The use of dental study models is an integral part of both dental practice and dental research. They provide a useful tool for teaching purposes and are essential for orthodontics, orthognathic surgery, extensive restorative work, and prosthodontics.

For medico-legal purposes the Consumer Protection Act 1987 states that it is necessary to retain all patient records for not less than 11 years[3] and the British Association of Orthodontists[4] recommends that study models should be kept for 11 years or until the patient is 26 years old. This leads to problems of storage in terms of space and cost, in addition to the risk of damage because of the brittle nature of dental casts. These problems highlight the need for an alternative method for storing study models.

Various methods have been employed in the three-dimensional (3D) assessment and recording of dental study models. These include Holography[5] and Moire Topography.[6,7]

Holography was introduced in 1948[8] and involved microscopy by reconstructed wavefronts. However, it was the work of Leith & Upatnieks[9] that revolutionized holography with the application of the laser beam. Holography allows direct measurement of 3D displacements of a few micrometres.[10–12]

A specifically designed holography camera is needed

Address for correspondence: Professor A. F. Ayoub, Oral and Maxillofacial Surgery, Head of Biotechnology and Craniofacial Research Group, Glasgow Dental Hospital and School, 378 Sauchiehall Street, Glasgow, G32 3JZ, Scotland, UK. E-mail: a.ayoub@dental.gla.ac.uk

to record the dental models and four holographic views: occlusal, front, right buccal, and left buccal are required for each model. Holograms can be expensive and difficult to produce, and although the image captured by holography is three-dimensional, it is stored in a static form and cannot be manipulated as a set of study models can.

The major problem with this technique is the poor quality of recording the details of the study models, particularly in the incisor region.[13] An advantage of holography is that films may be stored with medical records and it is a further step towards archiving dental study models. However, it cannot totally replace the original models.

Moire Topography has also been employed by dental researchers to store study models.[6,7] This is a contour mapping technique designed to produce successive contour lines directly on an object. However, resolution is poor, especially for dental morphology because of the difficulty of obtaining the fine pitch of contour lines.

It appears that these techniques cannot replace the use of the original methods. Also, there is still a need for a method to record the study models in digital format, which can be stored on a personal computer.

There are some studies in which images of dental casts scanned with various types of lasers have been stored and measured on a personal computer.[14–16] Motohashi & Kuroda[14] developed a 3D computer-aided system, and scanned dental study models with a slit-ray laser beam and Lu *et al.*[15] introduced a laser scanning 3D digitization system for dental casts using a special semiconductor laser. Hirogaki *et al.*[16] scanned dental casts using a line laser scanner and compared measurements on computer-reconstructed models with those on the actual casts. The difference was within 0.3 mm.

Ayoub *et al.*[1] introduced a photostereometric technique that is based on the use of stereo pairs of video cameras connected to a personal computer and special coloured illumination to record dental study models in digital format. The stored data can be converted into a stereolithographic format for the reconstruction of the study model if required. However, no formal study was carried out to measure the reconstructed accuracy of the 3D computer-generated images using this technique. The technique has also been employed to image the face, for use in maxillofacial assessment and surgical planning.[17]

This study was carried out to investigate the metric accuracy of the technique introduced by Ayoub *et al.*[1] for recording dental study models. The null hypothesis tested was that there was no statistically significant difference between direct measurements of dental casts compared with those obtained from computer-generated 3D images of the same study models.

Material and methods

Dental study models stored at Glasgow Dental Hospital and School were used for this study. It was decided that a difference of 0.5 mm would be taken as significant. A power value of 0.90 was chosen so that there was a high probability of detecting a significant difference should it exist; and it was calculated that a minimum of 20 dental study models should be used. There were 22 study models available for research and measurements were made, both manually and digitally on these models.

On each model six anatomical dental points were marked. Using Euclidean Distance Matrix Analysis,[2] the linear distances between the points were measured with an Orthomax Vernier calliper. A total of 15 measurements were made on each cast (Figure 1). The same points on each cast were measured eight times with at least a 1-day interval between measurements. The mean differences in measurements were calculated to assess intra-operator error in manual measurement.

Each study model was also captured in three dimensions using the biostereometric technique introduced by Ayoub *et al.*[1] The study models were placed on an adjustable Dental Surveyor table. Stereo pairs of video cameras connected to a personal computer were used to capture the images. The cameras were positioned 500 mm from the study model and 100 mm apart. Camera resolution was 576 × 768 monochrome pixels. The cameras were connected to a personal computer with a standard frame grabber, which converts a television picture to a digital array of numbers. The software package used was C3D-builder (University of Glasgow).

Due to the homogenous appearance of study models, a fine pattern of random dots was projected onto the casts with a slide projector. This provided the visible texture required by C3D-builder. For each model, two pairs of images were captured: one pair under normal

Measurements made between points

2–3	3–4	4–5	5–6
2–4	3–5	4–6	
2–5	3–6		
2–6			
1–6			

Total 15 measurements

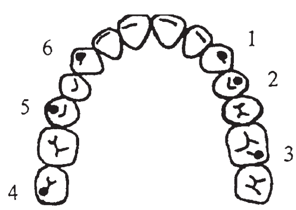

Fig. 1 Diagram of dental study model showing the system used for the measurement of selected points.

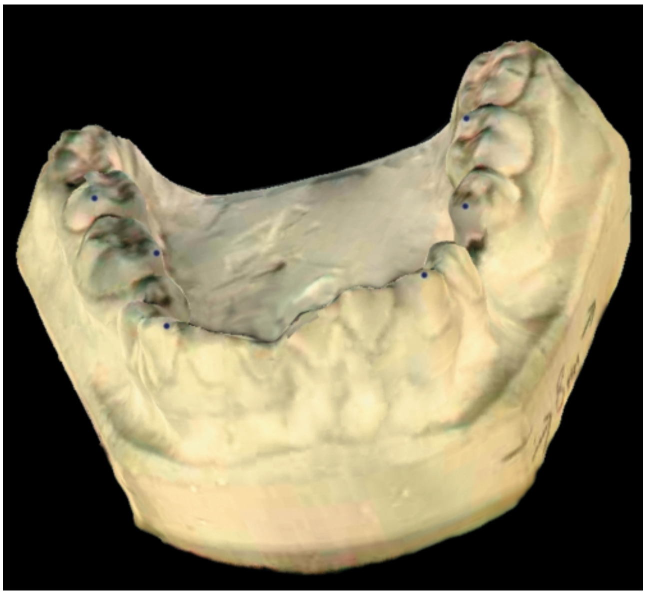

Fig. 2 View of a digitally stored model.

illumination and the other pair with texture projection. Individual capture time was 0.04 seconds.

Images were digitized and automatically loaded into the computer memory. The C3D-builder processed the texture-projected pair of images to produce a 3D surface reconstruction of the study model. A polygon mesh represented this.

To visualize the models the normally illuminated image was superimposed on the polygon cast. This allowed the measurement points that had been placed on the casts to be visualized.

The resulting cast can be viewed on the computer from any angle or position (Figure 2). This allows direct measurement of real distances, areas, volumes, and angles. A computer automated measuring tool was used to make the same measurements that had been carried out manually. The points on each cast were digitized and the distances between the points were calculated. This was carried out eight times for each cast, with at least a 1-day interval between measurements. The mean differences in measurements were calculated to assess the error of the method.

The mean differences in measurements made on the 3D images and on the actual study models were then compared. Statistical analysis was carried out using a two-sample *t*-test.

Results

The mean differences between manual measurements are shown in Table 1. There were variations when the same operator measured the same points at different times, although none of the differences were statistically significant ($P < 0.05$, two-sample *t*-test). The difference between measurements ranged from 0.10–0.48 mm (mean 0.17, SD 0.08). There will always be differences due to slight variation in the manual positioning of measuring callipers, even when measuring points are clearly marked.

Table 1 Variation in repeated direct measurements of the dental casts

Cast	Mean difference between measurements (mm)	SD	Probability levels two-sample *t* test	Significance of difference
1	0.22	0.05	$P = 0.87$	ns
2	0.15	0.13	$P = 0.96$	ns
3	0.10	0.12	$P = 0.97$	ns
4	0.12	0.05	$P = 0.99$	ns
5	0.18	0.12	$P = 0.97$	ns
6	0.18	0.05	$P = 0.95$	ns
7	0.18	0.15	$P = 0.86$	ns
8	0.12	0.05	$P = 0.98$	ns
9	0.15	0.13	$P = 0.94$	ns
10	0.10	0.08	$P = 0.99$	ns
11	0.15	0.24	$P = 0.95$	ns
12	0.20	0.08	$P = 0.98$	ns
13	0.20	0.18	$P = 0.83$	ns
14	0.28	0.10	$P = 0.90$	ns
15	0.12	0.15	$P = 0.90$	ns
16	0.10	0.10	$P = 0.98$	ns
17	0.48	0.62	$P = 0.93$	ns
18	0.20	0.08	$P = 0.98$	ns
19	0.10	0.08	$P = 0.99$	ns
20	0.12	0.10	$P = 0.98$	ns
21	0.10	0.08	$P = 0.87$	ns
22	0.18	0.12	$P = 0.97$	ns

Overall mean difference 0.17 mm, SD 0.08.

Table 2 demonstrates the differences when the same points were measured at different times on the 3D images. The differences were not statistically significant ($P < 0.05$, two-sample *t*-test). The range was 0.02–0.14 mm (mean 0.06, SD 0.03). With this technique, the operator must position the measuring tool on the landmarks on 3D images and so operator variation still exists. In this study, the variation in repeated 3D measurements was less than with repeated direct measurements.

The mean differences between measurements made directly on the study models and those made with the computer on the 3D images ranged between 0.16 and 0.38 mm (mean 0.27 mm, SD 0.06; Table 3). These differences were not statistically significant ($P < 0.05$, two-sample *t*-test).

Table 2 Variation in repeated measurements of the 3D images

Cast	Mean difference between measurements (mm)	SD	Probability levels two-sample *t* test	Significance of difference
1	0.04	0.04	$P = 1.00$	ns
2	0.14	0.07	$P = 0.98$	ns
3	0.09	0.11	$P = 0.97$	ns
4	0.08	0.02	$P = 0.98$	ns
5	0.12	0.08	$P = 0.94$	ns
6	0.11	0.10	$P = 0.97$	ns
7	0.03	0.01	$P = 1.00$	ns
8	0.07	0.04	$P = 0.97$	ns
9	0.05	0.02	$P = 1.00$	ns
10	0.04	0.04	$P = 1.00$	ns
11	0.02	0.01	$P = 1.00$	ns
12	0.04	0.03	$P = 1.00$	ns
13	0.02	0.00	$P = 1.00$	ns
14	0.10	0.05	$P = 0.97$	ns
15	0.06	0.05	$P = 0.99$	ns
16	0.03	0.04	$P = 0.99$	ns
17	0.08	0.06	$P = 0.98$	ns
18	0.02	0.02	$P = 1.00$	ns
19	0.03	0.02	$P = 0.99$	ns
20	0.06	0.03	$P = 1.00$	ns
21	0.06	0.06	$P = 0.91$	ns
22	0.03	0.02	$P = 0.99$	ns

Overall mean difference 0.06 mm, SD 0.03.

Table 3 Assessment of the difference between direct measurements made on dental casts and those made on 3D images

Cast	Mean difference between measurements (mm)	SD	Probability levels two-sample *t* test	Significance of difference
1	0.26	0.05	$P = 0.85$	ns
2	0.22	0.09	$P = 0.91$	ns
3	0.31	0.08	$P = 0.91$	ns
4	0.35	0.03	$P = 0.84$	ns
5	0.23	0.22	$P = 0.84$	ns
6	0.37	0.11	$P = 0.87$	ns
7	0.32	0.06	$P = 0.76$	ns
8	0.24	0.07	$P = 0.86$	ns
9	0.23	0.15	$P = 0.92$	ns
10	0.24	0.11	$P = 0.94$	ns
11	0.16	0.13	$P = 0.96$	ns
12	0.32	0.15	$P = 0.87$	ns
13	0.18	0.06	$P = 0.84$	ns
14	0.27	0.08	$P = 0.90$	ns
15	0.35	0.22	$P = 0.77$	ns
16	0.23	0.15	$P = 0.93$	ns
17	0.34	0.07	$P = 0.90$	ns
18	0.18	0.08	$P = 0.91$	ns
19	0.34	0.12	$P = 0.92$	ns
20	0.24	0.07	$P = 0.89$	ns
21	0.28	0.15	$P = 0.40$	ns
22	0.38	0.23	$P = 0.86$	ns

Overall mean difference 0.27 mm, SD 0.06.

Discussion

In the clinic dental study models are usually measured by hand, often with the use of measuring callipers, such as the Vernier calliper. This technique relies on the operator positioning the tips of the calliper on a specific landmark and reading the distance from the ruler on the calliper. The technique is therefore subject to intra- and inter-operator variation. In this study, one operator carried out all of the measurements and so only intra-operator variation was assessed. When the same operator measured the study models by hand on eight different occasions the difference in measurements of the same points ranged from 0.10–0.48 mm. None of the differences were statistically significant.

When the measurements are made on the 3D computer images operator variation still plays a role because the operator has to click on the points to be measured. However, the operator does not have to read a measuring scale since the computer calculates the distance between points. The variation between measurements of the same points on the computer (range 0.02–0.14 mm) was less than the manual measurement variation. Again, this intra-operator variation was not statistically significant. The overall mean difference in measurements was 0.17 mm for the hand measurements and 0.06 mm for measurements made on the 3D images. Although intra-operator variation did not affect either technique significantly, this variation was reduced with the use of the photostereometric technique described in this paper.

Ayoub *et al.*[1] estimated that using this technique dental study models could be digitized to a precision of 0.2 mm. The results of this formal study were only slightly higher at 0.27 mm. The differences between manual measurements and measurements made on 3D images were not statistically significant and were, in fact, well within the range of intra-operator variation when the study models were measured by hand (0.10–0.48 mm). It is unlikely that a difference of 0.27 mm would have a significant clinical impact. This figure is comparable with the difference of 0.3 mm recorded by Hirogaki *et al.*[16] In their study, models were laser scanned and measurements made on computer-reconstructed models were compared with those made on actual casts.

It appears that the photostereometric technique introduced by Ayoub *et al.*[1] is an accurate and reproducible method for recording, storing and measuring dental study models. At present, study models have to be kept as part of the patient's records for at least 11years.[1] However, once the medico-legal time requirements are fulfilled this technique would allow models to be digitized and stored on a personal computer. This would reduce problems in terms of the space and cost involved in the long-term mass storage of dental study models. Since accurate measurements can be made on the 3D images, the models may still be used in treatment review and dental research even after the actual models have been discarded.

If the actual dental cast was required at some point in the future there is provision for converting the file into a stereolithography format for physical reconstruction in plastic.[1] This is an area that merits further research.

Conclusions

This study assesses the accuracy of measurements made on digitized dental models using a technique developed for archiving study models and storing the three-dimensional data in digital format.[1]

The technique allows the study models to be stored and viewed on a personal computer. The digitized models can be viewed from various angles and positions; and measurements can be made to a precision of 0.27 mm.

There is variation in measurement related to the operator positioning the measuring points on the digitized casts (0.02–0.14 mm). However, this is less than the variation observed when a measuring calliper is placed directly onto actual study models (0.14–0.48 mm).

This technique could reduce problems of mass storage, whilst allowing the data to be used for treatment monitoring and auditing in orthodontics and orthognathic surgery. The digitized models could also be used for research purposes.

Acknowledgement

We would like to thank Svenja Hoff and Jean Christophe Nebill (Department of Computer Science, University of Glasgow) for their help with the production of images of the computer generated casts.

References

1. Ayoub AF, Wray D, Moos KF, Jin J, Niblett TB, Urquhart C, *et al.* A three-dimensional imaging system for archiving dental study casts: a preliminary report. *Int J Adult Orthod Orthognath Surg* 1997; **12**: 79–84.
2. Ayoub AF, Stirrups DR, Moos KF. Assessment of chin surgery by a coordinate free method. *Int J Oral Maxillofac Surg* 1994; **23**: 6–10.
3. British Dental Association. *Advice Sheet B1: ethics in dentistry*. London: BDA, 1995.
4. Machen DE. Legal aspects of orthodontic practice: risk management concepts. British Association of Orthodontists. *BAO Newsletter*, September 1991; 4.
5. Ansley DA. Techniques for pulsed laser holography of people. *Appl Optics* 1970; **9**: 815–821.
6. Takasaki H. Moire topography. *Appl Optics* 1970; **9**: 1467–1472.
7. Kanazawa E, Sekikawa M, Ozaki T. Three-dimensional measurements of the occlusal surfaces of upper molars in a Dutch population. *J Dent Res* 1984; **63**: 1298–1301.
8. Gabor G. A new microscopic principle. *Nature* 1948; **161**: 777–778.
9. Leith EN, Upatnieks J. Photography by laser. *Scient Am* 1965; **212**: 24–35.
10. Wedendal PR, Bjelkhagen HI. Dental holographic interferametry *in vivo* utilising a Ruby Laser System. *Acta Odontol Scand* 1974; **32**: 345–356.
11. Young JM, Altschuler BR. Laser holography in dentistry. *J Prosth Dent* 1977; **38**: 216–225.
12. Ryden H, Bjelkhagen H, Martensson B. Tooth position measurements on dental casts using holographic images. *Am J Orthod* 1982; **81**: 310–313.
13. Harradine N, Stephens C. Holograms as substitutes for orthodontic study casts: a pilot clinical trial. *Am J Ortho Dentofac Orthod* 1990; **98**: 110–116.
14. Motohashi N, Kuroda T. A 3D computer-aided design system applied to diagnosis and treatment planning in orthodontics and orthognathic surgery. *Eur J Orthod* 1999; **21**: 263–274.
15. Lu P, Li Z, Wang Y, Chen J, Zhao J. The research and development of a non-contact 3D laser dental model measuring and analysing system. *Chin J Dent Res* 2000; **3**: 7–14.
16. Hirogaki Y, Sohmura T, Satoh H, Takahashi J, Takada K. Complete 3D reconstruction of dental cast shape using perceptual grouping. *1EEE Trans Med Imaging* 2001; **20**: 1093–1101.
17. Ayoub AF, Siebert P, Moos KF, Wray D, Urquhart C, Niblett TB. A vision based 3D capture system for maxillofacial assessment and surgical planning. *Br J Oral Maxillofac Surg* 1998; **36**: 353–357.