Original Article

The Relationship between Digital Model Accuracy and Time-Dependent Deformation of Alginate Impressions

Toros Alcan[a]; Cenk Ceylanoğlu[b]; Bekir Baysal[b]

ABSTRACT

Objectives: To investigate the effects of different storage periods of alginate impressions on digital model accuracy.

Materials and Methods: A total of 105 impressions were taken from a master model with three different brands of alginates and were poured into stone models in five different storage periods. In all, 21 stone models were poured and immediately were scanned, and 21 digital models were prepared. The remaining 84 impressions were poured after 1, 2, 3, and 4 days, respectively. Five linear measurements were made by three researchers on the master model, the stone models, and the digital models. Time-dependent deformation of alginate impressions at different storage periods and the accuracy of traditional stone models and digital models were evaluated separately.

Results: Both the stone models and the digital models were highly correlated with the master model. Significant deformities in the alginate impressions were noted at different storage periods of 1 to 4 days. Alginate impressions of different brands also showed significant differences between each other on the first, third, and fourth days.

Conclusions: Digital orthodontic models are as reliable as traditional stone models and probably will become the standard for orthodontic clinical use. Storing alginate impressions in sealed plastic bags for up to 4 days caused statistically significant deformation of alginate impressions, but the magnitude of these deformations did not appear to be clinically relevant and had no adverse effect on digital modeling. (*Angle Orthod.* 2009;79:30–36.)

KEY WORDS: Digital model; Alginate impression; 3Shape

INTRODUCTION

Study models provide a three-dimensional replica of malocclusion during any stage of treatment, as well at the final outcome. Despite all associated benefits, these study models have some disadvantages in terms of storage, durability, and transferability.

Many attempts have been made to replace plaster study models. In the mid 1990s, three-dimensional (3D) scanning technology was introduced, and study models[1–7] were transformed into a digital format. Since then, software technology has refined this approach, and digital orthodontic models have become commercially available.[8–14] However, this technology is associated with other problems, such as the scarcity of digital model supplier companies, the time required to ship impressions to those companies, and questions on the accuracy of the final digital model.

Currently, five companies worldwide are producing digital models commercially. Three of these companies are in the United States, one is in The Netherlands, and one is in Poland. These companies accept high-quality alginate impressions with 100+ hours' dimensional stability and disposable impression trays.

Besides the digital model supplier companies, some software companies, such as 3Shape (3Shape A/S, Copenhagen, Denmark; scans only stone models), Laserdenta (Laserdenta AG, Basel, Switzerland; scans both stone models and impressions), and INUS Dental Scanning Solution (INUS Technology, Inc, Seoul, Korea), supply 3D model scanners and orthodontic software for individual clinical practice.

As instructed by the digital model supplier companies, alginate impressions are delivered in 1 day, re-

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Accepted: December 2007. Submitted: October 2007.

DOI: 10.2319/100307-475.1

gardless of the location of their origin; in case of any delay, the impressions retain dimensional stability for up to 100 hours, or even up to 10 days. However, the International Standard (IS) for alginate impression materials (ISO 1563: 1990E) contains no specification for dimensional stability and thus places no requirement on manufacturers to state dimensional stability properties on their labels.

Dimensional stability was defined by Nicholls[15] as "the ability (of a material) to maintain accuracy over time." Further, this paper defines the result of loss of accuracy as "distortion," and "the relative movement of a single point, or group of points, away from some originally specified reference position such that permanent deformation is apparent." Dental alginates, similar to all hydrocolloids, tend to distort over time as they lose (by evaporation and syneresis) or gain (by imbibition) water, thereby contracting or expanding. Even when stored under conditions of 100% humidity, an alginate impression will contract, indicating that processes other than dehydration, including polymerization and syneresis, are involved.[15–19]

Therefore, the best results are obtained when dental alginate impressions are poured after 10 minutes, to avoid distortion from initial expansion and elastic deformation, and before 1 hour, to avoid distortion from alginate contraction or expansion due to water movement and syneresis.[20,21]

Another question is the accuracy of digital modeling. Several studies have shown that linear measurements on digital models and plaster models have significant differences, but the magnitude of these differences does not appear to be clinically relevant. The overall conclusion of these studies is that digital models are acceptable alternatives to stone casts for the routine measurements used in orthodontic practice.[22–34] On the other hand, no study has evaluated the possible time-dependent deformation of alginate impressions during their shipment to the companies involved.

The two aims of this study are as follows:

- To evaluate the accuracy of digital models produced by the 3Shape system
- To test the dimensional stability of three different brands of alginates for durations of 1, 2, 3, and 4 days in a laboratory environment that simulates shipping conditions

MATERIALS AND METHODS

In this study, a maxillary dental model (D85SDP-200; Kilgore International Inc, Coldwater, Mich) was used as a master model. Five artificial reference points were prepared on the master model to increase the reproducibility of measurements with the use of a conical bur on the following:

Right and left first molar mesiobuccal cusp tips
Right and left canine cusp tips
Left second premolar buccal cusp tip

Three different brands of alginates—(1) Cavex (Holland BV, Haarlem, The Netherlands), (2) Orthoprint (Zhermack Spa, Badia Polesine [RO], Italy), and (3) Tropicalgin (Zhermack)—were used to produce stone models of the master model. Thirty-five impressions with each alginate were taken from the master model, constituting a sum of 105 impressions. All impressions were taken by the same researcher with the use of plastic trays of the same size (DuraLock Plus Impression Trays 501-005U; Ortho Technology, Tampa, Fla). Tray adhesives were not used.

Alginates were mixed manually, with strict adherence to manufacturers' instructions. Impressions were not rinsed with water or immersed in any disinfecting solutions. The 105 impressions were divided into five equal groups, as follows:

Immediate group: 7 Cavex + 7 Orthoprint + 7 Tropicalgin = 21 impressions
First day group: 7 Cavex + 7 Orthoprint + 7 Tropicalgin = 21 impressions
Second day group: 7 Cavex + 7 Orthoprint + 7 Tropicalgin = 21 impressions
Third day group: 7 Cavex + 7 Orthoprint + 7 Tropicalgin = 21 impressions
Fourth day group: 7 Cavex + 7 Orthoprint + 7 Tropicalgin = 21 impressions

The impressions of the immediate group were poured into stone within 1 hour with the use of Fujirock EP type 4 dental stone (GC, Tokyo, Japan) mixed in a vacuum mixer (Twister; Renfert GmbH, Hilzingen, Germany) and were allowed to set, with the tray not inverted. The impressions of the first, second, third, and fourth day groups were placed in sealed plastic bags in accordance with digital model companies' instructions. The brand of alginate, the number of the model, and the day and exact time the impressions were taken were recorded on the sealed bags. The sealed impression bags of all groups were stored in a dark room at standard room temperature (23 ± 2°C [ISO 4823: 1992 E]). The impressions of the first day were poured after 24 hours, the second day after 48 hours, the third day after 72 hours, and the fourth day after 96 hours. At the end of four different storage times, 105 stone models had been obtained.

Digital Model Production

The 21 stone models of the immediate group were transformed into digital format by a 3D model scanner (3Shape D250; 3Shape A/S). The digital models were analyzed by 3Shape Orthoanalyzer, version 1.0, soft-

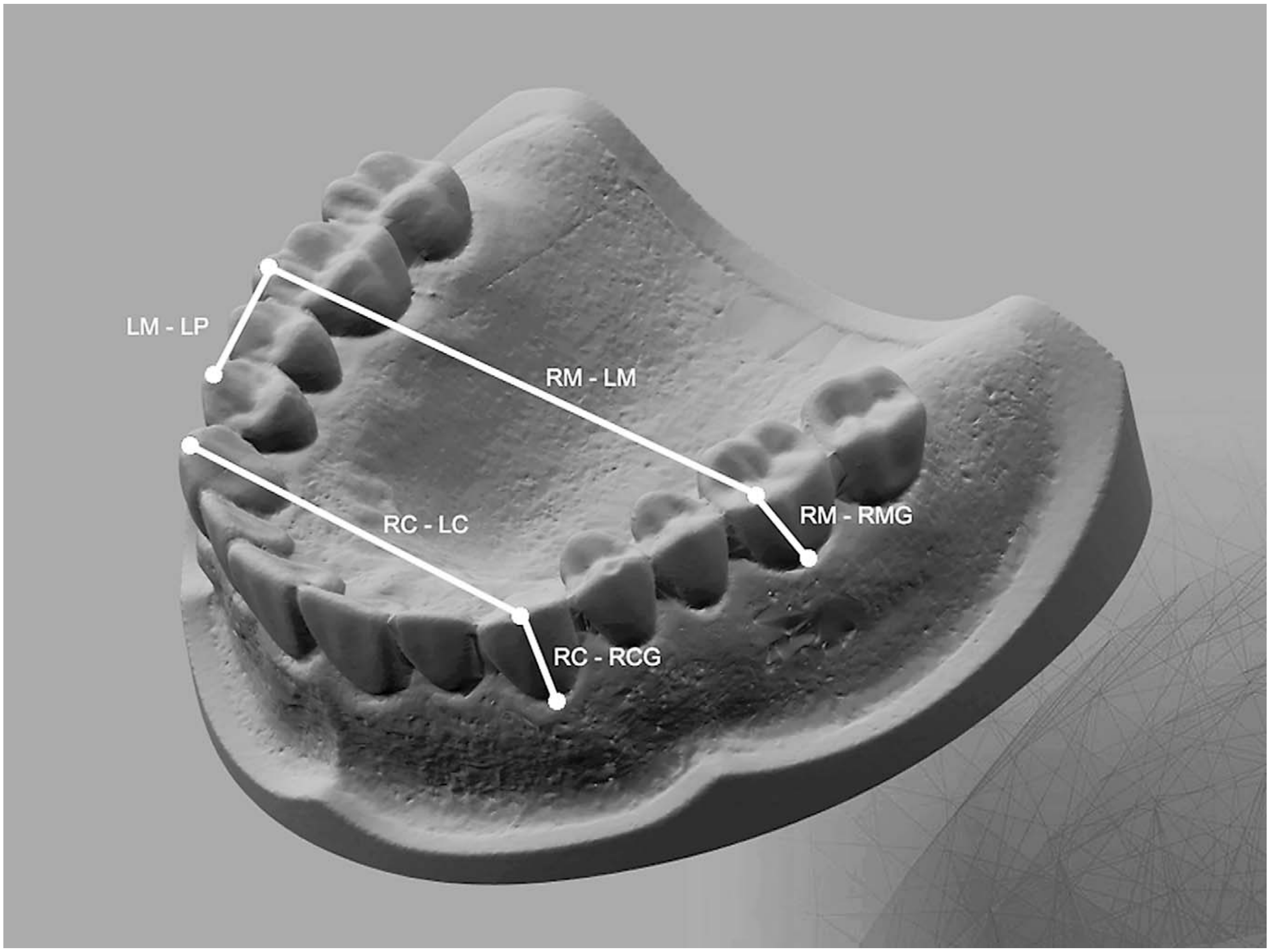

Figure 1. Reference points and linear measurements on the digital model: RM: Right first molar mesiobuccal cusp tip; LM: Left first molar mesiobuccal cusp tip; RC: Right canine cusp tip; LC: Left canine cusp tip; LP: Left second premolar buccal cusp tip; RMG: Deepest point of right first molar buccal gingival curve; RCG: Deepest point of right canine buccal gingival curve.

ware (3Shape A/S). The remaining 84 models were not transformed into digital models.

Measurement Parameters

Seven points (five artificial and two anatomic) and five linear measurements were used to analyze the master, stone, and digital models. The measurement points and the linear measurements are shown in Figure 1. The sum of linear measurements was calculated to create an overall linear measurement for each model.

The master model, 21 stone models of the immediate group, and 21 digital models were analyzed by three different researchers to achieve a gold standard, whereas the remaining 84 stone models of the first, second, third, and fourth days were analyzed by two different researchers. Each measurement was repeated three times. Digital models were measured with the measurement tool provided by 3Shape Orthoanalyzer software to the nearest 0.01 mm (10 μm). The master model and the stone models were measured with an electronic caliper (Masel, Bristol, Pa) to an accuracy of 0.01 mm (10 μm) (Figure 2).

Statistical Methods

In this study, statistical analyses were completed with the use of NCSS PASS 2007 statistical and data analysis software (NCSS, Kaysville, Utah). Two-way random intraclass correlation coefficient, 95% confidence interval (CI), absolute difference, and absolute percentage were calculated to determine the following:

Interobserver and intraobserver reliability
Reliability between the master model and the stone models
Reliability between the master model and the digital models
Reliability between the stone models and the digital models

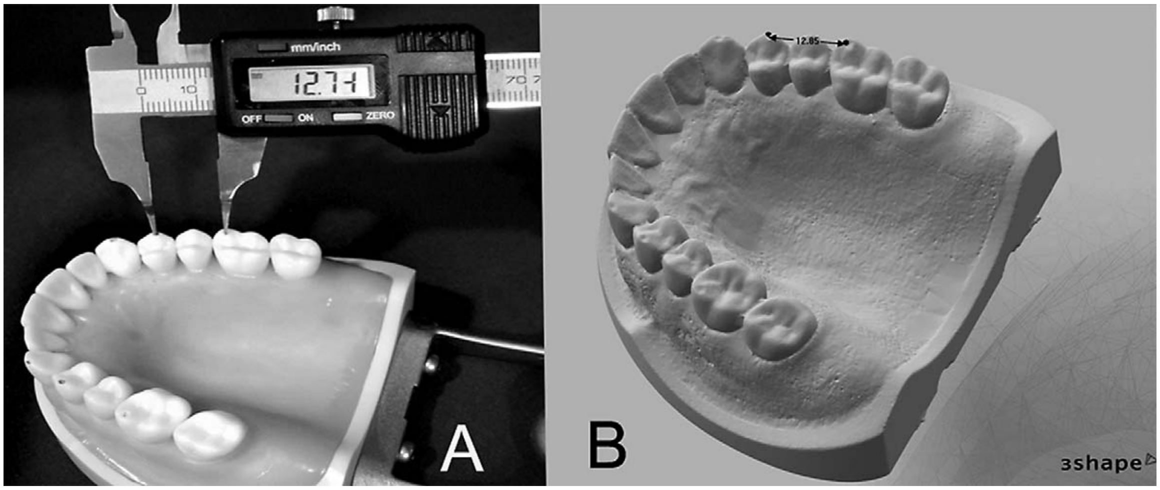

Figure 2. (A) Linear measurement with a digital caliper on the master model. (B) Linear measurement with 3Shape software on the digital model.

Table 1. Interexaminer Reliability

	Master Model		21 Stone Models		21 Digital Models	
	Interclass Correlation Coefficient	95% CI[a]	Interclass Correlation Coefficient	95% CI[a]	Interclass Correlation Coefficient	95% CI[a]
RM-LM	0.963	0.84–0.99	0.773	0.654–0.855	0.74	0.604–0.834
RC-LC	0.874	0.65–0.97	0.721	0.672–0.894	0.786	0.619–0.872
RM-RMG	0.836	0.74–0.93	0.82	0.754–0.926	0.847	0.767–0.902
RC-RCG	0.877	0.66–0.92	0.815	0.715–0.964	0.752	0.623–0.842
LM-LP	0.865	0.72–0.94	0.73	0.619–0.873	0.845	0.674–0.932
Overall	0.967	0.924–0.985	0.978	0.945–0.989	0.975	0.952–0.991

[a] CI indicates confidence interval.

The differences between alginate brands were calculated by the Kruskal-Wallis test, and the differences between the stone models of five groups were calculated by the Friedman test. Results were evaluated at $P < .05$ significance and 95% CI.

RESULTS

The reliability of the observers revealed high intraclass correlation coefficients in master model measurements, measurements on 21 stone models of the immediate group, and measurements on 21 digital models (Table 1).

The correlation coefficient for the measurement of the master model and the 21 stone models of the immediate group was 0.975. The absolute difference value between the master model and the 21 stone models was 0.152 ± 0.125 mm, and the absolute percentage was 1.285% ± 1.529% for the overall measurements (Table 2).

The correlation coefficient for the measurement of the master model and the 21 digital models was 0.977. The absolute difference value between the master model and the 21 digital models was 0.095 ± 0.053 mm, and the absolute percentage was 0.695% ± 0.637% for the overall measurements (Table 3).

The correlation coefficient for the measurement of the 21 digital models and the 21 stone models of the immediate group showed a high level of reliability with the value of 0.989 (Table 4). The absolute difference value between the 21 stone models of the immediate group and the 21 digital models was 0.199 ± 0.164 mm, and the absolute percentage was 0.73% ± 0.3% for the overall measurements (Table 4).

The differences in overall measurements of the stone models poured from three different alginates immediately and after 1, 2, 3, and 4 days of storage time are shown in Table 5 and Figure 3.

DISCUSSION

A digital model is essentially a replica of a replica. The errors and the problems may be doubled because the digital model process has two phases. The first phase involves taking an impression and pouring a model (mouth-to-stone model phase), and the second

Table 2. Comparison Between Measurements Made on 21 Stone Models and the Master Model

	Similarity		Difference	
	Interclass Correlation Coefficient	95% CI[a]	Absolute Difference, mm	Absolute Percentage, %
RM-LM	0.768	0.654–0.941	0.096 ± 0.064	0.183 ± 0.121
RC-LC	0.736	0.698–0.909	0.087 ± 0.068	0.24 ± 0.188
RM-RMG	0.883	0.731–0.948	0.274 ± 0.164	3.189 ± 1.886
RC-RCG	0.749	0.684–0.898	0.231 ± 0.096	2.235 ± 0.93
LM-LP	0.786	0.658–0.914	0.074 ± 0.047	0.577 ± 0.363
Overall	0.975	0.932–0.989	0.152 ± 0.125	1.285 ± 1.529

[a] CI indicates confidence interval.

Table 3. Comparison Between Measurements Made on Digital Models and the Master Model

	Similarity		Difference	
	Interclass Correlation Coefficient	95% CI[a]	Absolute Difference, mm	Absolute Percentage, %
RM-LM	0.739	0.645–0.896	0.063 ± 0.056	0.12 ± 0.106
RC-LC	0.793	0.655–0.941	0.099 ± 0.041	0.273 ± 0.115
RM-RMG	0.859	0.783–0.951	0.11 ± 0.076	1.314 ± 0.9
RC-RCG	0.761	0.686–0.874	0.103 ± 0.047	1.023 ± 0.467
LM-LP	0.823	0.681–0.915	0.097 ± 0.031	0.742 ± 0.235
Overall	0.977	0.949–0.991	0.095 ± 0.053	0.695 ± 0.637

[a] CI indicates confidence interval.

Table 4. Comparison Between Measurements Made on Digital Models and Stone Models of the Immediate Group

	Similarity		Difference	
	Interclass Correlation Coefficient	95% CI[a]	Absolute Difference, mm	Absolute Percentage, %
RM-LM	0.786	0.615–0.864	0.381 ± 0.158	0.73 ± 0.3
RC-LC	0.774	0.629–0.887	0.123 ± 0.068	0.34 ± 0.19
RM-RMG	0.75	0.667–0.812	0.097 ± 0.069	1.16 ± 0.83
RC-RCG	0.744	0.626–0.833	0.055 ± 0.038	0.55 ± 0.38
LM-LP	0.809	0.787–0.930	0.336 ± 0.104	2.62 ± 0.83
Overall	0.989	0.975–0.993	0.199 ± 0.164	0.73 ± 0.3

[a] CI indicates confidence interval.

Table 5. Changes in Overall Measurements of Stone Models Poured into Three Different Brands of Alginates in Five Different Storage Periods

Overall Measurements	Cavex[a]	Orthoprint[b]	Tropicalgin[c]	KW	*P* Value
Immediate group	120.23 ± 0.26	119.97 ± 0.39	119.88 ± 0.44	6.04	.48
First day	119.92 ± 0.37	119.62 ± 0.38	119.55 ± 0.42	6.52	.036
Second day	119.66 ± 0.33	119.55 ± 0.32	119.31 ± 0.67	2.03	.362
Third day	119.72 ± 0.27	119.62 ± 0.31	118.99 ± 0.46	14.97	.006
Fourth day	119.15 ± 0.26	119.43 ± 0.28	118.92 ± 0.41	11.47	.003
Fr	34.191	10.111	25.392		
P	.0001	.039	.0001		

[a] Cavex Holland BV, Haarlem, The Netherlands.
[b] Ortho Technology Inc, Tampa, Florida.
[c] Zhermack Spa, Badia Polesine (RO), Italy.

phase consists of scanning a stone model (stone-to-digital model phase). In addition to evaluating the accuracy of 3D scanning alone, the accuracy of impressions and different alginate behaviors should be evaluated throughout the digital model process. This study sought to investigate the complete process, from the impression taking stage to the stage of 3D model analyses.

To determine the observers' reliability, three sets of measurements on the master model, 21 stone models

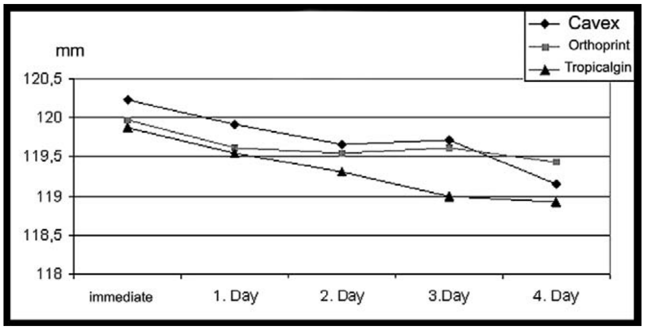

Figure 3. Changes in overall measurements of stone models over 4 days of storage time.

of the immediate group, and 21 digital models were compared with the use of the intraclass correlation coefficient, the absolute difference, and the absolute percentage. Results showed a high level of interobserver reliability, thus setting up a gold standard (Table 1).

Tomassetti et al[22] stated that distinguishing the proper landmarks was difficult with the OrthoCAD (Cadent Inc, Carlstadt, NJ) and Quick Ceph Systems (Quick Ceph Systems Inc, San Diego, Calif). Moreover, in his review, Houston[35] points out that the greatest source of random error involves difficulty in identifying a particular landmark. This leads to the issue of reproducibility of the computerized analysis.

Hence, in this study, investigators used a master model to represent the maxillary dental arch, plastic impression trays of the same size, and one brand of dental stone, to lessen the variables; investigators also prepared artificial reference points on teeth to enhance the reproducibility of measurements. Both the measurements made on these reference points (RM-LM, RC-LC, LM-LP) and the measurements made on anatomic points (RM-RMG, RC-RCG) showed high degrees of interobserver correlation, revealing that researchers were fairly accurate in measuring anatomic points as well (Table 1). The artificial reference points did not have an additive effect on accuracy in this study. These results may be due to the high quality of the models (both digital and stone) and the care and skill of the observers, which are important factors, as mentioned in Houston's study.[35]

Deformation of alginates occurs in multiple linear directions. However, the aim of this study was to show the *overall effect* of time-dependent deformation of alginate impressions on all linear parameters in digital modeling, rather than clarifying its effects on each parameter *separately.* Thus, although the statistical results of each linear parameter are shown on each table, together with the overall parameter, the present discussion is founded on its effects on the overall parameter rather than on its effects on each linear parameter separately.

A high correlation between the master model and the stone models of the immediate group shows that the traditional approach to the "mouth-to-stone model phase" is a reliable procedure. The absolute difference in the overall measurements is 0.152 mm, and the mean absolute percentage error is 1.285%. This leads to a 0.11 mm error on the mesiodistal measurement of an 8 mm wide tooth. These values can be accepted as within clinical tolerance in orthodontic practice (Table 2).

A high correlation was also noted between the measurements of 21 stone models of the immediate group and 21 digital models (stone-to-digital model phase). The absolute difference value was 0.199 mm, and the absolute percentage was 0.011% for the overall measurements (Table 4). This result shows that the scanning procedure is much more reliable than the taking of alginate impressions. However, one should still take an impression and pour into the stone model to obtain a digital model.

The differences between measurements of the master model and the digital models were also evaluated and highly correlated. The absolute difference between the digital models and the master model was as small as 0.095 mm, and the mean absolute percentage was 0.695%. It is interesting to note that these results showed that digital models, which we call "the replica of the replica," were more similar to the master model than were the stone models. This may be due to the evaluation of linear changes in terms of absolute values (Table 3).

The effects of the time-dependent deformation of alginates on digital model accuracy were evaluated throughout the measurements on stone models of all groups because the stone models of the immediate group were highly correlated with their digital replicas. Depending on the measurements of stone models poured from the three brands of alginates, investigators learned that significant deformations occurred during 4 days of storage (Table 5 and Figure 3). These three alginates also showed significant differences among one other at the first, third, and fourth days but not on the second day in terms of overall linear measurements. However, regarding the overall values in Table 5, these differences are very small in terms of millimeters, which can be accepted in clinical tolerance and in orthodontic analyses.

As a result, storing these three brands of alginate impressions in sealed plastic bags up to 4 days had no adverse effect on digital modeling. One can expect that developments in 3D scanning technology will continue to occur until direct 3D scanning of the full dentition becomes a clinically practicable method for orthodontists.

CONCLUSIONS

- Digital orthodontic models are as reliable as traditional stone models and probably will become the standard for orthodontic clinical use.
- Storing alginate impressions in sealed plastic bags for up to 4 days had no adverse effects on the digital model.
- This new technology is still alginate dependent.

ACKNOWLEDGMENT

The authors thank Norayr Set for his complimentary help in scanning procedures.

REFERENCES

1. Van der Linden FP, Boersma H, Zelders T, Peters KA, Raaben JH. Three-dimensional analysis of dental casts by means of the Optocom. *J Dent Res.* 1972;51:1100.
2. Schwaninger B, Schmidt RL, Hurst RV. Holography in dentistry. *J Am Dent Assoc.* 1977;95:814–817.
3. Burstone CJ. Dr. Charles J. Burstone on the uses of the computer in orthodontic practice (part 1). *J Clin Orthod.* 1979;13:442–453.
4. Rudge SJ. A computer program for the analysis of study models. *Eur J Orthod.* 1982;4:269–273.
5. Rydén H, Bjelkhagen H, Mårtensson B. Tooth position measurements on dental casts using holographic images. *Am J Orthod.* 1982;81:310–313.
6. Harradine N, Suominen R, Stephens C, Hathorn I, Brown I. Holograms as substitutes for orthodontic study casts: a pilot clinical trial. *Am J Orthod Dentofacial Orthop.* 1990;98:110–116.
7. Mårtensson B, Rydén H. The Holodent system, a new technique for measurement and storage of dental casts. *Am J Orthod Dentofacial Orthop.* 1992;102:113–119.
8. Joffe L. OrthoCAD: digital models for a digital era. *J Orthod.* 2004;31:344–347.
9. Marcel TJ. Three-dimensional on-screen virtual models. *Am J Orthod Dentofacial Orthop.* 2001;119:666–668.
10. Pair JW, Luke L, White S, Atkinson K, Englehart R, Brennan R. Variability of study cast assessment among orthodontists. *Am J Orthod Dentofacial Orthop.* 2001;120:629–638.
11. Redmond WR. Digital orthodontic office: 2001. *Semin Orthod.* 2001;7:266–273.
12. Redmond WR. Wireless orthodontics. *Am J Orthod Dentofacial Orthop.* 2001;120:325–327.
13. Redmond WR. Digital models: a new diagnostic tool. *J Clin Orthod.* 2001;35:386–387.
14. Marcel T. Our digital model experience: a six-month Orthocad user report: practice management diary. *PCSO Bull.* 2001;73:1 and 4.
15. Nicholls J. The measurement of distortion: theoretical considerations. *J Prosthet Dent.* 1977;37:578–586.
16. Phillips RW, Ito BY. Properties of alginates. *J Am Dent Assoc.* 1958;43:1.
17. Hampson EL. Contraction of alginates. *Br Dent J.* 1955;99:37–41.
18. Miller MW. Syneresis in alginate impression materials. *Br Dent J.* 1975;139:425–430.
19. Coleman RM, Hembree JH, Weber FN. Dimensional stability of irreversible hydrocolloid impression material. *Am J Orthod.* 1979;75:438–446.
20. Skinner EW, Pomes CE. Syneresis in hydrocolloids. *J Am Dent Assoc.* 1946;33:1253.
21. Anseth KS, Bowman CN, Bannon-Peppas L. Mechanical properties of hydrogels and their experimental determination. *Biomaterials.* 1996;17:1647–1657.
22. Tomassetti JJ, Taloumis LJ, Denny JM, Fischer JR. A comparison of 3 computerized Bolton tooth-size analyses with a commonly used method. *Angle Orthod.* 2001;71:351–357.
23. Garino F, Garino GB. Comparison of dental arch measurements between stone and digital casts. *World J Orthod.* 2002;3:250–254.
24. Zilberman O, Huggare JA, Parikakis KA. Evaluation of the validity of tooth size and arch width measurements using conventional and three-dimensional virtual orthodontic models. *Angle Orthod.* 2003;73:301–306.
25. Santoro M, Galkin S, Teredesai M, Nicolay OF, Cangialosi TJ. Comparison of measurements made on digital and plaster models. *Am J Orthod Dentofacial Orthop.* 2003;124:101–105.
26. Brosky ME, Major RJ, DeLong R, Hodges JS. Evaluation of dental arch reproduction using three-dimensional optical digitization. *J Prosthet Dent.* 2003;90:434–440.
27. Quimby ML, Vig KW, Rashid RG, Firestone AR. The accuracy and reliability of measurements made on computer-based digital models. *Angle Orthod.* 2004;74:298–303.
28. Costalos PA, Sarraf K, Cangialosi TJ, Efstratiadis S. Evaluation of the accuracy of digital model analysis for the American Board of Orthodontics objective grading system for dental casts. *Am J Orthod Dentofacial Orthop.* 2005;128:624–629.
29. Stevens DR, Flores-Mir C, Nebbe B, Raboud DW, Heo G, Major PW. Validity, reliability, and reproducibility of plaster vs. digital study models: comparison of peer assessment rating and Bolton analysis and their constituent measurements. *Am J Orthod Dentofacial Orthop.* 2006;129:794–803.
30. Mayers M, Firestone AR, Rashid R, Vig KW. Comparison of peer assessment rating (PAR) index scores of plaster and computer-based digital models. *Am J Orthod Dentofacial Orthop.* 2005;128:431–434.
31. Rheude B, Sadowsky PL, Ferriera A, Jacobson A. An evaluation of the use of digital study models in orthodontic diagnosis and treatment planning. *Angle Orthod.* 2005;75:300–304.
32. Whetten JL, Williamson PC, Heo G, Varnhagen C, Major PW. Variations in orthodontic treatment planning decisions of Class II patients between virtual 3-dimensional models and traditional plaster study models. *Am J Orthod Dentofacial Orthop.* 2006;130:485–491.
33. Cha BK, Choi JI, Jost-Brinkmann PG, Jeong YM. Applications of three-dimensionally scanned models in orthodontics. *Int J Comput Dent.* 2007;10:41–52.
34. Mullen SR, Martin CA, Ngan P, Gladwin M. Accuracy of space analysis with e-models and plaster models. *Am J Orthod Dentofacial Orthop.* 2007;132:346–352.
35. Houston WJ. The analysis of errors in orthodontic measurements. *Am J Orthod.* 1983;83:382–389.