


Position Accuracy of Implant Analogs on 3D Printed Polymer versus Conventional Dental Stone Casts Measured Using a Coordinate Measuring Machine

Marta Revilla-León, DDS, MSD ^{1,2}, Óscar Gonzalez-Martín, DDS, MS,^{3,4} Javier Pérez López, RDT,^{1,5} José Luis Sánchez-Rubio, RDT,^{1,6} & Mutlu Özcan, DDS, DMD, PhD⁷

¹Revilla Research Center, Madrid, Spain

²Graduate Prosthodontics, University of Washington School of Dentistry, Seattle, WA

³Department of Periodontics, University of Pennsylvania School of Dental Medicine, Philadelphia, PA

⁴Department of Periodontology, University Complutense of Madrid, Madrid, Spain

⁵Tecnica Studio Laboratory, Madrid, Spain

⁶3D Dental Laboratory, Madrid, Spain

⁷Division of Dental Materials, Center for Dental and Oral Medicine, University of Zürich, Zürich, Switzerland

Keywords

3D printing; additive manufacturing technologies; definitive implant cast; direct light processing technology; implant prostheses; inject technology; multijet printing; stereolithography technology.

Correspondence

Dr. Marta Revilla León, Calle Berlin 14, 28922 Madrid, Spain.

E-mail: revilla@revillaresearchcenter.com.

Marta Revilla-León ORCID

<http://orcid.org/0000-0003-2854-1135>.

The authors did not have any conflict of interest in any of the materials used in this study.

Accepted June 20, 2017

doi: 10.1111/jopr.12708

Abstract

Purpose: To compare the accuracy of implant analog positions on complete edentulous maxillary casts made of either dental stone or additive manufactured polymers using a coordinate measuring machine (CMM).

Material and Methods: A completely edentulous maxillary model of a patient with 7 implant analogs was obtained. From this model, two types of casts were duplicated, namely conventional dental stone (CDS) using a custom tray impression technique after splinting (N = 5) and polymer cast using additive manufacturing based on the STL file generated. Polymer casts (N = 20; n = 5 per group) were fabricated using 4 different additive manufacturing technologies (multijet printing-MJP1, direct light processing-DLP, stereolithography-SLA, multijet printing-MJP2). CMM was used to measure the correct position of each implant, and distortion was calculated for each system at x-, y-, and z-axes. Measurements were repeated 3 times per specimen in each axis yielding a total of 546 measurements. Data were analyzed using ANOVA, Sheffé tests, and Bonferroni correction ($\alpha = 0.05$).

Results: Compared to CMM, the mean distortion (μm) ranged from 22.7 to 74.9, 23.4 to 49.1, and 11.0 to 85.8 in the x-, y-, and z-axes, respectively. CDS method (x-axis: 37.1; z-axis: 27.62) showed a significant difference compared to DLP on the x-axis (22.7) ($p = 0.037$) and to MJP1 on the z-axis (11.0) ($p = 0.003$). Regardless of the cast system, x-axes showed more distortion (42.6) compared to y- (34.6) and z-axes (35.97). Among additive manufacturing technologies, MJP2 presented the highest (64.3 ± 83.6), and MJP1 (21.57 ± 16.3) and DLP (27.07 ± 20.23) the lowest distortion, which was not significantly different from CDS (32.3 ± 22.73) ($p > 0.05$).

Conclusion: For the fabrication of the definitive casts for implant prostheses, one of the multijet printing systems and direct light processing additive manufacturing technologies showed similar results to conventional dental stone. *Clinical significance:* Conventional dental stone casts could be accurately duplicated using some of the additive manufacturing technologies tested.

When fabricating an implant prosthesis, a definitive cast should be an accurate representation of the 3D position of the implants in the patient's mouth.¹ Typically, this cast is obtained from a dental impression that is a negative imprint of the mouth.² When four or more implants are present, a splinting technique is recommended in order to obtain a more accurate working cast.³⁻⁶

The American Society for Testing and Materials (ASTM) has defined additive manufacturing (AM) as "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies."⁷ The ASTM international committee F42 on AM technologies has determined seven AM categories: stereolithography (SLA), material jetting (MJP), material



Figure 1 Complete edentulous maxillary definitive cast with 7 implant analogs.

extrusion or fused deposition modelling (FDM), binder jetting, powder bed fusion (PBF), sheet lamination, and direct energy deposition.⁸ The growing development of AM technologies has allowed different applications in prosthetic dentistry.⁹⁻¹¹ The SLA and MJF technologies in particular, are the most common categories used for manufacturing dental models.⁹⁻¹² SLA technology is based on 3D CAD design that turns the polymer into a solid object through the repeated solidification of liquid resin through a UV laser.¹³⁻¹⁵ A different approach as an alternative to laser for UV polymerization of the material is the use of digital light projection (DLP) sources. In the DLP method, the silhouette of each layer is projected onto a surface of the resin that is polymerized by light either in the visible or the UV spectrum.^{15,16} On the other hand, FDM technology builds parts layer-by-layer from bottom up by heating and extruding a thermoplastic filament from a printing nozzle. Once extruded into a bead, the material is immediately set at high temperatures of the machine and layered on a platform. The nozzle repeats the extruding and melting, layer by layer, until the object is complete.¹⁷ The MJF is different in that a carriage jets photopolymers onto the workspace that are then polymerized using UV light. After a thin layer is created, the process repeats itself by jetting additional layers until the object is fully fabricated.^{12,15,18}

The major conceptual difference between the 3D printed AM models and the conventional dental stone (CDS), is the design of the implant analogs. On the CDS models, the implant analog is designed as a retentive element so that it gets stuck and does not move when pouring the dental implant impression. Additionally, when manufacturing a 3D printed AM model, the digital implant analog is placed after the model is manufactured, and as a consequence, the digital implant analog design is retrievable from the cast.

The objective of this study was to compare the accuracy of implant analog positions on completely edentulous maxillary casts either made of dental stone or additive-manufactured polymers using a coordinate measuring machine (CMM). The null hypothesis tested was that there would be no statistically significant difference between the model duplication methods at the x-, y-, and z-axes.



A



B



C

Figure 2 (A) Printed metal splint on the definitive cast, (B) printed polymer custom tray on the definitive cast, and (C) conventional dental stone cast obtained duplicating the definitive cast through conventional impression technique.

Table 1 Summary of manufacturers and technical details of cast fabrication

Groups	CDS	MJP1	DLP	SLA	MJP2
Printer (manufacturer)		Projet 3510MP (3D Systems, Rock Hill, SC)	Prodways ProMaker D35 (Dreve, Unna, Germany)	Infinident (Sirona, Bensheim, Germany)	Object (Stratasys, Eden Prairie, MN)
Technology	Conventional Type IV Dental Stone (Fujirock EP; GC, Tokyo, Japan) Impression with polyether, splinting, custom tray	Multijet printing	Direct-light processing	Stereolithography	Multijet printing
Layer thickness (μm)	–	35	50	50–100	35
Resolution (x-, y-, z-axis)	–	HDX: 375 × 450 × 790 DPI	784 × 784 × 1016 DPI	–	HQ: 600 × 600 × 1600 DPI

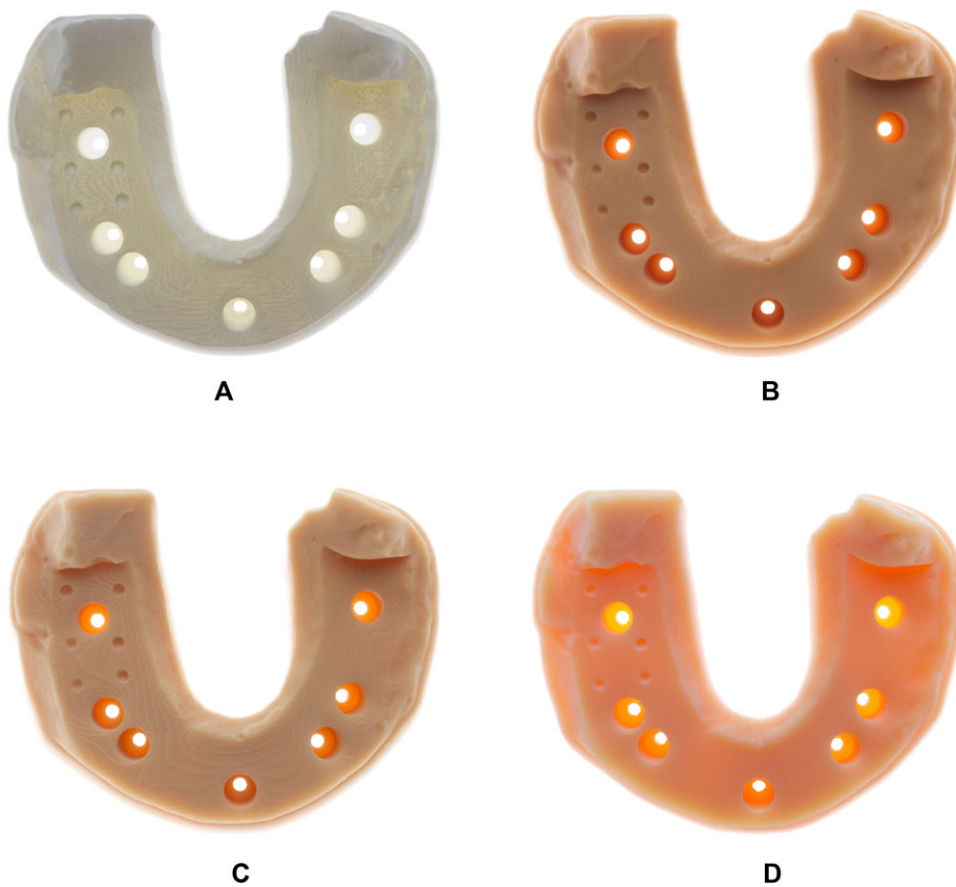


Figure 3 3D printed model using (A) MJP1, (B) DLP, (C) SLA, and (D) MJP2 additive technologies.

Materials and methods

Specimen preparation

One edentulous maxillary definitive cast of a patient was selected. The maxillary cast presented seven implant analogs (Tissue Level RN Straumann Implant analogs; Straumann,

Basel, Switzerland) (Fig 1). From this model, two types of casts were duplicated: conventional dental stone (CDS) using a custom tray impression technique after splinting (N = 5) and polymer cast using additive manufacturing based on the STL file generated. Polymer casts (N = 20; n = 5 per group) were fabricated using four different additive manufacturing

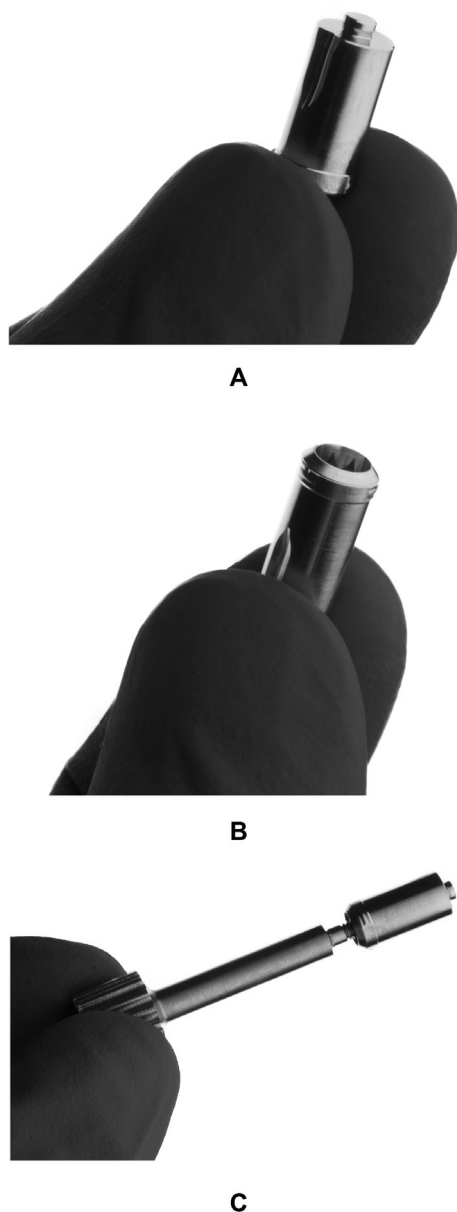


Figure 4 (A) Apical view of the digital implant analog, (B) coronal view of the digital implant analog, (C) screwdriver to hold and position the implant analog on the printed cast.

technologies (multijet printing-MJP1, direct light processing-DLP, stereolithography-SLA, multijet printing-MJP2). CMM was used to measure the correct position of each implant, and distortion was calculated for each system at x-, y-, and z-axes.

For the specimen fabrication in the CDS group, a conventional rigid splinting framework and a custom tray impression technique were employed.¹⁹ The impression was poured with Type IV dental stone (GC Fujirock EP; GC, Tokyo, Japan) after mixing 22 ml water with 110 g dental stone under vacuum for 30 seconds. The cast was recovered after the dental stone had completely set (Figs 2A, B).

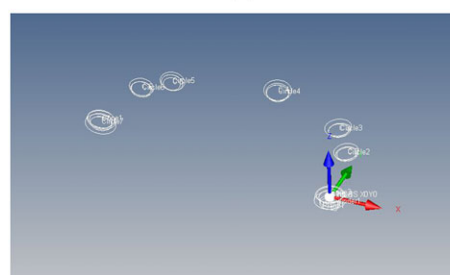
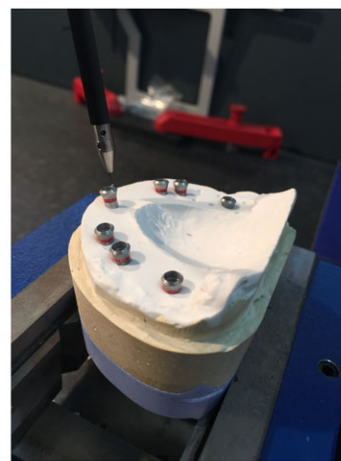


Figure 5 (A) Analysis of the implant analog position on the x-, y-, and z-axes using a CMM machine, (B) best-fitting calculation using the specific software.

For the specimens of polymer cast groups, a tactile (DS10 Scanner; Renishaw, Gloucestershire, UK) and optical scanner (Renishaw DS20, Meditec, Gloucestershire, UK) with specific dental CAD software (Exocad GmbH, Hessen, Germany) was used to obtain the stereolithography (STL) file of the maxillary definitive cast. The same STL file was used to fabricate all other polymer casts using additive technologies for four different additive manufacturing technologies (MJP1, DLP, SLA, MJP2) (Table 1, Fig 3). For all the polymer casts, the same digital implant analogs (Straumann RN ELOS implant analog; ELOS Medtech, Göteborg, Sweden) were used (Fig 4).

Measurements

Each group contained 5 models, yielding a total of 25 models having 7 implants each. A coordinate measuring machine (CMM) was used to evaluate the position of the implant analogs on the x-, y-, and z-axes. The position of the center point of all the implant replicas was measured with the CMM (Carl Zeiss Industrielle Messtechnik GmbH, Oberkochen, Germany) in an independent laboratory (Laboratorio de Ingeniería Dimensional S.L., Madrid, Spain). The manufacturer described the nominal linear accuracy of the machine to be within 1 μ m in all axes. The measuring machine and procedures were similar, as described earlier.²⁰ In brief, the master model was measured and used as a reference for comparison of the 25 casts having implant analogs (Fig 5).

Table 2 Mean values for distortion (μm), standard deviations and confidence intervals of each group at x-, y-, and z-axes

Axes	Groups	N	Mean (μm)	Standard deviation	Confidence interval (95%)	
					Lower bound	Upper bound
x	CDS	35	37.1	22.8	29.3	44.9
	MJP1	35	23.6	21.2	16.3	30.8
	DLP	35	22.7	17.1	16.8	28.5
	SLA	35	54.9	37.1	42.2	67.7
	MJP2	35	74.9	81.7	46.8	102.9
	Total	175	42.6	47.1	35.6	49.7
y	CDS	35	32.2	21.7	24.7	39.6
	MJP1	35	30.1	19.2	23.6	36.7
	DLP	35	23.4	13.4	18.8	28.1
	SLA	35	49.1	37.9	36.0	62.1
	MJP2	35	38.4	34.1	26.7	50.1
	Total	175	34.7	27.9	30.5	38.8
z	CDS	35	27.6	23.7	19.5	35.8
	MJP1	35	11.0	8.5	8.1	13.9
	DLP	35	35.1	30.2	24.7	45.5
	SLA	35	20.3	18.4	13.9	26.7
	MJP2	35	85.8	135	39.4	132.2
	Total	175	36.0	67.9	25.8	46.1

Table 3 Multiple comparisons for the x-, y-, and z-axes between the experimental groups according to Bonferroni correction ($\alpha = 0.05$)

Axis	Groups	Differences of means (μm)	p Value	
x	CDS	MJP1	13.543	0.113
		DLP	14.457	*0.037
		SLA	-17.838	0.165
		MJP2	-37.752	0.110
y	CDS	MJP1	1.990	1.000
		DLP	8.733	0.375
		SLA	-16.914	0.222
		MJP2	-6.238	0.987
z	CDS	MJP1	16.610	*0.003
		DLP	-7.476	0.938
		SLA	7.295	0.801
		MJP2	-58.162	0.148

The CMM had a scanning head equipped with a 0.5 mm stylus (0.1 N) that could be positioned anywhere within the working space of the CMM. The data for each cylinder were condensed to a position at the center point of the cylinder in the x-, y-, and z- axes. Three-dimensional (x-, y-, and z- axes) directions of displacement of the center points were calculated in μm in absolute values. The 3D position of the implant analogs of the definitive cast was used as a reference to calculate the discrepancy between all implant analogs on each model using a specific CAD software (Geomatic; 3D Systems, Rock Hill, SC).

Statistical analysis

Statistical analysis was performed with SPSS Statistics for Windows V20 (SPSS, Chicago, IL). Data (μm) were analyzed using ANOVA, Sheffé tests, and Bonferroni correction ($\alpha = 0.05$).

Results

Compared to CMM, the mean distortion (μm) ranged from 22.7 to 74.9, 23.4 to 49.1, and 11.0 to 85.8 in the x-, y-, and z-axes, respectively (Table 2). CDS method (x-axis: 37.1; z-axis: 27.6) showed significant difference compared to DLP on the x-axis (22.7) ($p = 0.037$) and to MJP1 on the z-axis (11.0) ($p = 0.003$) (Table 3). Regardless of the cast system, the x-axis showed more distortion (42.6) compared to the y- (34.7) and z-axes (35.97). Among additive manufacturing technologies MJP2 showed the highest (64.3 ± 83.6), and MJP1 (21.57 ± 16.3) and DLP (27.07 ± 20.23) the lowest distortion, being not significantly different from CDS (32.3 ± 22.73) ($p > 0.05$).

Discussion

This study analyzed the accuracy of implant analogs on casts obtained from conventional procedures where the impression was made using polyether followed by establishing the splint and fabricating the custom tray for complete-arch implant impression. The casts were duplicated using different additive manufacturing technologies, and accuracy was compared to dental stone using CMM. In the present study, there were significant differences between systems on the x- and z-axes, so the null hypothesis could be rejected.

CMM analysis is widely used in dentistry to calculate the implant analog position on the x-, y-, and z-axes, and is considered an accurate method to assess the dimensional discrepancies of the implant analog position between the different dental models.^{21,22} Previous studies, most of which focused on treatment planning and diagnosis for oral and maxillofacial surgery and orthodontics have analyzed the accuracy and precision of AM technologies.²³⁻³² However, to the best knowledge of the authors, to date, there is no published study that analyzed the accuracy of the digital implant analog position on a 3D AM cast. When duplicating a cast with conventional procedures, the mean distortion was 37.1 (27.8), 32.1 (21.7), and 27.6 (23.7) μm , while for the AM casts it was 44.0 (39.3), 35.2 (26.3), and 38.1 (48.0) μm for the x-, y-, and z-axes, respectively. Yet, only two of the four technologies showed no significant difference on the x-, y-, and z-axes compared to the control group. Hence, based on the results obtained, the duplication of a master cast with AM technologies based on MJP1 and DLP could show similar distortion compared to CDS.

On the z-axis, the MJP1 method showed significantly better results compared to the CDS method. Interestingly, although, MJP1 and MJP2 methods were based on the same multijet printing technology with a layer thickness of 35 μm and the latter had a better resolution, the accuracy results were more favorable with the MJP1 on the z-axes. On the other hand, compared to the CDS method, the DLP method presented significantly lower distortion on the x-axes, although the layer thickness of 50 μm

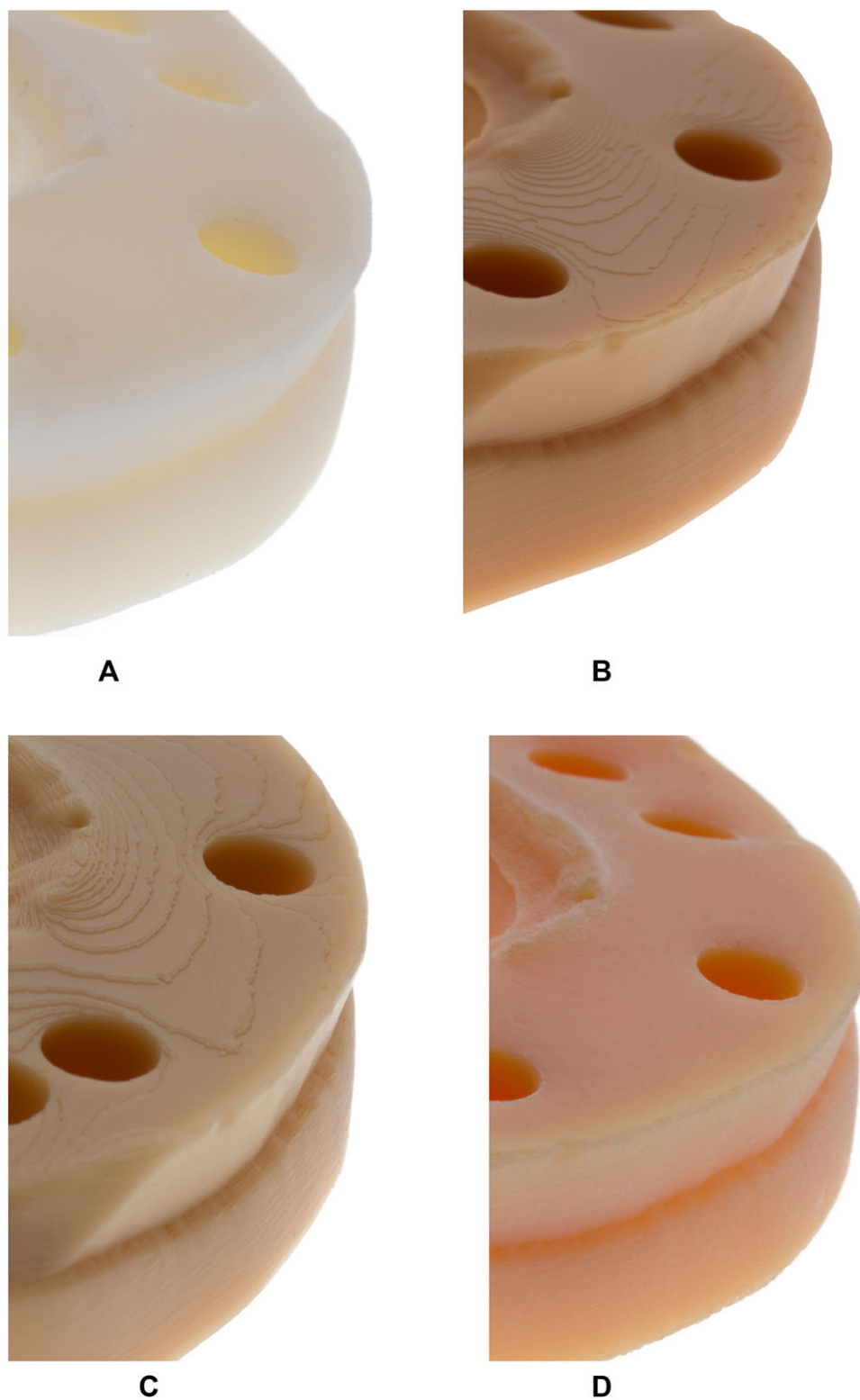


Figure 6 Closer view of the surface texture of a specimen manufactured using (A) MJ1, (B) DLP, (C) SLA, and (D) MJ2.

was slightly higher than those of MJP1, MJP2, and SLA. These results could be attributed to multiple variables such as building orientation, intensity power of the polymerization UV light source, and post-processing procedures. Nevertheless, among all AM technologies, MJP2 showed the highest standard deviations, up to 135 μm , compared to those of other systems (DLP: 30.2; SLA: 37.9). The conventional CDS system in turn, demonstrated mean (37.1) and standard deviations (23.7) less than 35 μm in all x-, y-, and z-axes, indicating that meticulous handling of Type IV dental stone may also deliver acceptable accuracy.

For the specimen fabrication of the CDS group, the conventional procedures selected to duplicate the master cast have been demonstrated to be accurate and represent the clinical procedures needed to make a complete-arch impression of multiple implants.^{19,21,33,34} For manufacturing the polymer casts, a master cast was digitized using a specific tactile dental scanner, and the same STL file was used to fabricate all the polymer casts. In this study, different manufacturing technologies that employed various processing parameters and post-processing procedures that were previously shown to affect the accuracy and repeatability outcomes were compared.³⁵ However, these results were obtained from standard geometric shapes where implant-related parameters were not studied.

One important factor that could influence the accuracy of the printed polymer is the layer building orientation of the 3D object (Fig 6). A previous report demonstrated that the building orientation of the 3D printed object influences the mechanical properties where vertically printed specimens, with the layer oriented perpendicular to the load direction exhibiting a higher compressive strength than material printed horizontally.³⁶ When manufacturing an AM cast for complete-arch implant prostheses, the accuracy of the housing of the digital implant analog of the cast would determine the accuracy of the implant analog position on the cast. Currently, digital implant analogs show variations in design depending on the brand. For the present study, one digital implant analog brand was selected, and the digital implant analogs used were always in the same position for all measurements. As a definitive cast, a real patient case was selected without considering the angulation, depth, and distance between the implants, and this needs further investigation. Similarly, the number of implants, retention, and stability on the 3D-printed PCs could further affect the results.

The incorporation of additive manufacturing technologies enables duplication of a definitive cast where implant analogs could be easily reused or replaced when damaged. Furthermore, STL files of the definitive casts of the patients could be stored in the cloud in its corresponding physical space.

Conclusions

For the duplication of the definitive casts for implant prostheses, one of the multijet printing systems and direct-light processing additive manufacturing technologies tested showed similar accuracy compared to the models obtained using conventional dental stone.

Acknowledgments

The authors would like to thank Mr. Fernando García, from Metrologia Ltd., Madrid, Spain, for his assistance with the CMM measurements.

References

- Rosenstiel SF, Land MF, Fujimoto J: Working casts and dies. In: Rosenstiel SF, Land MF, Fujimoto J (eds): *Contemporary Fixed Prosthodontics* (ed 3). St Louis, Mosby, 2001, pp. 434–441
- Wee AG, Aquilino SA, Schneider RL: Strategies to achieve fit in implant prosthodontics: a review of the literature. *Int J Prosthodont* 1999;12:167–178
- Ivanhoe JR, Adrian ED, Krantz WA: An impression technique for osseointegrated implants. *J Prosthet Dent* 1991;66:410–411
- Kim S, Nicholls JI, Han CH, et al: Displacement of implant components from impressions to definitive casts. *Int J Oral Maxillofac Implants* 2006;21:747–755
- Lee H, So JS, Hochstedler JL, et al: The accuracy of implant impressions: a systematic review. *J Prosthet Dent* 2008;100:285–291
- Papaspyridakos P, Benic GI, Hogsett VL, et al: Accuracy of implant casts generated with splinted and nonsplinted impression techniques for edentulous patients: an optical scanning study. *Clin Oral Impl Res* 2012;23:676–681
- Alcisto J, Enriquez A, Garcia H, et al: Tensile properties and microstructures of laser-formed Ti-6Al-4V. *J Mater Eng Perform* 2011;20:203–212
- ASTM, Committee F42 on Additive Manufacturing Technologies, West Conshohocken, Pa. 2009 Standard terminology for additive manufacturing – general principles and terminology. ISO/ASTM52900-15
- Fleming PS, Marinho V, Johal A: Orthodontic measurements on digital study models compared with plaster models: a systematic review. *Orthod Craniofac Res* 2011;14:1–16
- Rossini G, Parrini S, Castorflorio T, et al: Diagnostic accuracy and measurement sensitivity of digital models for orthodontic purposes: a systematic review. *Am J Orthod Dentofacial Orthop* 2016;149:161–170
- Stansbury JW, Idacavage MJ: 3D printing with polymers: Challenges among expanding options and opportunities. *Dent Mater* 2016;32:54–64
- Torabi K, Farjood E, Hamedani S: Rapid prototyping technologies and their applications in prosthodontics, a review of literature. *J Dent* 2015;16:1–9
- Apparatus for production of three-dimensional objects by stereolithography. US Patent 4575330; 1986
- Jacobs PF: *Rapid Prototyping and Manufacturing: Fundamentals of Stereolithography* (ed 1). Dearborn, MI, Society of Manufacturing Engineers, 1992, pp. 49–61
- Horn TJ, Harrysson OL: Overview of current additive manufacturing technologies and selected applications. *Sci Prog* 2012;95:255–282
- Liska R, Schuster M, Infuhr R, et al: Photopolymers for rapid prototyping. *J Coatings Technol Res* 2007;4:505–510
- Groth C, Kravitz ND, Jones PE, et al: The three dimensional printing technology. *J Clin Orthod* 2014;48:475–485
- Hofmann M: 3D printing gets a boost and opportunities with polymer materials. *ACS Macro Lett* 2014;3:382–386
- Revilla-León M, Sánchez-Rubio JL, Özcan M: Impression technique for complete arch with multiple implants using additive manufacturing technologies. *J Prosthet Dent* 2017;117:714–720

20. Örtorp A, Jemt T, Bäck T, et al: Comparisons of precision of fit between cast and CNC milled titanium implant frameworks for the edentulous mandible. *Int J Prosthodont* 2003;16:194-200
21. Tan KB, Rubenstein JE, Nicholls JI, et al: Three-dimensional analysis of the casting accuracy of one-piece, osseointegrated implant-retained prostheses. *Int J Prosthodont* 1993;6:346-363
22. Jemt T, Rubenstein JE, Carlsson L, et al: Measuring fit at the implant prosthodontic interface. *J Prosthet Dent* 1996;75:314-325
23. Silva DN, de Oliveira MG, Meurer E, et al: Dimensional error in selective laser sintering and 3D-printing of models for craniomaxillary anatomy reconstruction. *J Craniomaxillofac Surg* 2008;36:443-449
24. Ibrahim D, Broilo TL, Heitz C, et al: Dimensional error of selective laser sintering, three-dimensional printing and PolyJet models in the reproduction of mandibular anatomy. *J Craniomaxillofac Surg* 2009;37:167-173
25. Leifert MF, Leifert MM, Efstratiadis SS, et al: Comparison of space analysis evaluations with digital models and plaster dental casts. *Am J Orthod Dentofacial Orthop* 2009;136:16.e1-16.e4
26. Katatny EI, Masood SH, Morsi YS: Error analysis of FDM fabricated medical replicas. *Rapid Prototyp J* 2010;16:36-43
27. Abizadeh N, Moles DR, O'Neill J, et al: Digital versus plaster study models: How accurate and reproducible are they? *J Orthod* 2012;39:151-159
28. Salmi M, Paloheimo K-S, Tuomi J, et al: Accuracy of medical models made by additive manufacturing (rapid manufacturing). *J Craniomaxillofac Surg* 2013;41:603-609
29. Kasparova M, Grafova L, Dvorak P, et al: Possibility of reconstruction of dental plaster cast from 3D digital study models. *Biomed Eng Online* 2013;12:49
30. Hazeveld A, Huddleston Slater JJR, et al: Accuracy and reproducibility of dental replica models reconstructed by different rapid prototyping techniques. *Am J Orthod Dentofacial Orthop* 2014;145:8-15
31. Cho SH, Schaefer O, Thompson GA, et al: Comparison of accuracy and reproducibility of casts made by digital and conventional methods. *J Prosthet Dent* 2015;113:310-315
32. Rossini G, Parrini S, Castrolforio T, et al: Diagnostic accuracy and measurement sensitivity of digital models for orthodontic purposes: a systematic review. *Am J Orthod Dentofacial Orthop* 2016;149:161-170
33. Bergin JM, Rubenstein JE, Mancl L, et al: An in vitro comparison of photogrammetric and conventional complete-arch implant impression techniques. *J Prosthet Dent* 2013;110:243-251
34. Braian M, Jimbo R, Wennerberg A: Production tolerance of additive manufacturing polymeric objects for clinical applications. *Dent Mater* 2016;32:853-861
35. Alharbi N, Osman R, Wismeijer D: Effects on build orientation on the mechanical properties of 3D-printed complete coverage interim dental restorations. *J Prosthet Dent* 2016;115:760-767