Comparison of the Accuracy of Three-Dimensional Printed Casts, Digital, and Conventional Casts: An *In Vitro* Study

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Abstract

Objectives The integration of computer-aided design and manufacturing technologies in diagnosis, treatment planning, and fabrication of prosthetic restoration is changing the way in which prosthodontic treatment is provided to patients. The aim of this study was to compare the accuracy of three-dimensional (3D) printed casts produced from the intraoral scanner using stereolithographic (SLA) 3D printing technique, their digital replicas, and conventional stone casts.

Materials and Methods In this *in vitro* study, a typodont of maxillary and mandibular arches with full dentate ivory teeth was used as a reference cast. The typodont was digitized using Trios 3Shape intraoral scanner to create digital casts. The digital files were converted into 3D printed physical casts using a prototyping machine that utilizes the stereolithography printing technology and photocurable polymer as printing material. Linear measurements (mesiodistal and occlusocervical) and interarch measurements (intercanine and intermolar) were made for digital and prototyped models and were compared with the original stone casts. The reference teeth were canines, first premolars and second premolars in the maxillary and mandibular arches on the right and left sides. The measurements on printed and conventional casts were done by digital caliper while on digital casts; Geomagic Qualify software was used.

Statistical Analysis One-way analysis of variance (ANOVA) was used to compare measurements among groups.

Results Digital casts showed significantly higher error than the other two groups in all linear and interarch measurements. The mean errors of the digital cast in occlusocervical (OC) and mesiodistal (MD) measurements (0.016 and 0.006, respectively) were higher compared with those in the other two groups (OC, 0.004 and 0.007 and MD, 0.003 and 0.005 [$p < 0.0001$ and $p = 0.02$, respectively]). Also, digital mean error in intermolar width (IMW) and intercanine width (ICW) (0.142 and 0.113, respectively) were greater than the other two groups (IMW, 0.019 and 0.008 and ICW, 0.021 and 0.011 [$p < 0.0001$]). However, the errors were within the acceptable clinical range.

Conclusion The 3D printed casts may be considered as a substitute for stone casts with clinically acceptable accuracy that can be used in diagnosis, treatment planning, and fabrication of prosthetic restorations.

Keywords
- digital casts
- intraoral scanner
- three-dimensional printing

Introduction

Fabrication of master casts is a critical step to obtain the final prosthodontic restoration or prosthesis. They provide a stable and accurate representation of human dentition and their surrounding structures.[1] Despite their importance, they have several drawbacks, such as the need for a storage area, the possibility of wear or fracture of stone, and the difficulty in communication between laboratory and dental professionals.[2-4]

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Several studies were done to search for alternatives to conventional stone casts to avoid the previously mentioned disadvantages. Production of master model can be done by capturing secondary impression through direct intraoral scanners manufacturing the final restoration without master model fabrication.[5,6] Also after capturing digital impression, master cast can be produced by sending the standard tessellation language (STL) file to produce physical model by three-dimensional (3D) printer. With optical scanners, it is possible to create digital models by directly scanning the patient's teeth or indirectly scanning the cast or impression.[7-10]

Digital casts allow prosthodontists to perform diagnosis, treatment planning, and fabrication of the final restoration virtually by computer aided appliance manufacturing.[11,12] Also, they allow digital casts to completely replace conventional casts in case when a physical representation of the cast is needed for legal purposes or prosthesis design.[13,14] With rapid prototyping, it is now possible to fabricate physical casts from digital files. In this technology, computer aided machines create physical casts from substrate materials in an additive or subtractive manner depending on the original geometry of the digital casts.[15,16]

Additive rapid prototyping (or 3D printing) is the process of building solid objects from digital files by incremental layering. The basic idea involves slicing the digital model into thin slices with sophisticated software and sending these slices to a 3D printer controlled by computer.[17] Additive technology includes different manufacturing techniques, namely, fused deposition modeling (FDM), stereolithography (SLA), digital light projector (DLP), poly jet photopolymer (PPP), selective electron beam melting (SEBM), and laser powder forming techniques.[18,19]

Digital casts and rapid prototyped replicas are becoming increasingly popular among prosthodontics as a part of modern trends toward incorporating modern technologies into every day practice.[13,14,20,21]

However, clinical technology has to be tested before it can be implemented into clinical practice. This study was conducted to assess the accuracy of digital casts acquired from a light desktop scanner and their rapid prototyped replicas. The study hypothesis was that the accuracy of printed casts was not significantly different from that of digital and conventional stone casts.

Materials and Methods

A typodont cast (D95SDP-200; Kilgore International, Inc., Coldwater, Michigan, United States) with full set of maxillary and mandibular ivory teeth was used in this study as the reference cast. Polyvinylsiloxane impression was taken for the typodont model and poured in stone according to manufacturer instructions. Five conventional stone casts were created and their bases were trimmed according to bite registration (►**Fig. 1**).

Digital Cast Preparation

The typodont casts (reference casts) were scanned using intraoral dental scanner (Trios 3Shape) in the following three steps: first maxillary and mandibular casts were scanned separately; the second step involved articulating the maxillary and mandibular arches by utilizing the "bite registration algorithm." Third and finally, digital casts (n = 5) were exported in STL file format to be integrated into space analysis software.

Rapid Prototyping

The digital casts were sent to SLA 3D printer (ProJet 6000; 3D Systems, Rock Hill, South Carolina, United States) and printed casts were produced (n = 5) using photocurable liquid resin (VisiJet SL Clear; 3D Systems Inc., Rock Hill, SC, United States) as printing material (►**Fig. 2**).

Measuring Procedure

The following linear measurements were taken: mesiodistal (MD) and occlusocervical (OC) for first molar, first premolar and canine in addition to intermolar width (IMW) and intercanine width (ICW) on both arches and sides by the same operator (►**Fig. 3**).

Reference, conventional and prototyped casts were measured using digital caliper with sharpened peaks (series 500 Digimatic ABSolute Caliper, Mitutoyo Corporation, Kawasaki, Japan) according to the method described by Hunter and Priest.[22] Anatomical contact points and cusps tips were marked with a fine pencil to improve accuracy. Digital casts were measured using 3D Geomagic imaging software (Raindrop Geomagic Inc., 3D Systems, Rock Hill, South Carolina,

Fig. 1 Maxillary and mandibular conventional stone casts.

Fig. 2 Three-dimensional printed mandibular cast.

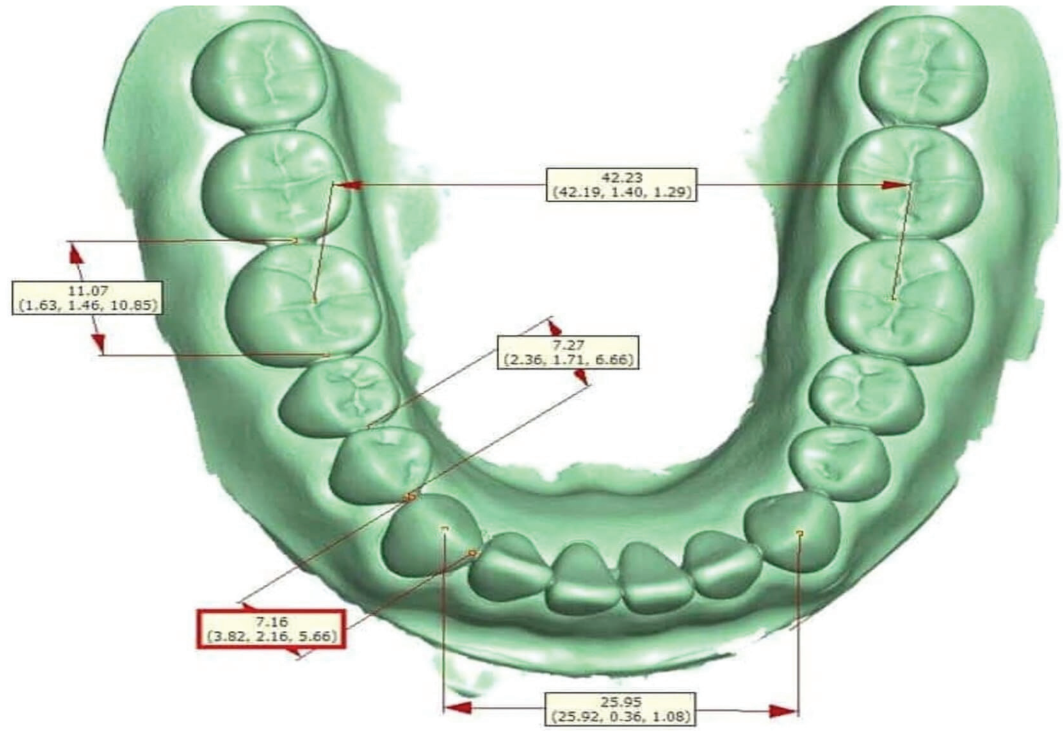

Fig. 3 Digital cast with mesiodistal, intercanine, and intermolar measurements.

United States) analysis; zoom and rotation functions were utilized when needed to gain better visualization of landmarks.

Validity was considered as the extent to which digital and prototyped casts measured against the stone casts "the gold standard."[23] The clinically acceptable limit of differences between the tested cast and stone casts is < 0.5 mm for teeth width, and < 5% for mean of arch dimensions.[11,23-27]

Statistical Analysis

Absolute errors were calculated as measurement (measurement in reference cast). Kolmogorov–Smirnov test and normality plots were used to check normality. One-way analysis of variance (ANOVA) was used to assess differences in errors among groups followed by post hoc pairwise comparisons using Tukey's test in case of significant differences. Significance level was set at 5%. IBM SPSS for Windows version 22.0 (IBM Corp., Armonk, New York, United States) was used for statistical analysis.

Results

►**Table 1** shows the comparison of errors among the study groups. The errors ranged from 0.003 to 0.142 mm for different measurements. In OC, the errors of digital cast were significantly higher than the errors of the other two groups, where the mean of the digital cast = 0.016 compared with 0.004 and 0.007 for the other two groups ($p < 0.0001$). Similarly, in MD measurements, the error of digital casts (mean = 0.006) was significantly greater than the error of printed casts (mean = 0.003) but similar to those of conventional casts (mean = 0.005) with overall significant difference ($p = 0.02$). For IMW and ICW, digital casts had significantly greater errors (mean = 0.142 in IMW and 0.113 in ICW) compared with

Table 1 Comparison of measurement errors relative to reference cast among the study groups

	Error compared with reference cast Mean (SD)			*p*-Value
	Printed	Conventional	Digital	
OC	0.004 (0.006)[a]	0.007 (0.007)[b]	0.016 (0.007)[c]	<0.0001*
MD	0.003 (0.005)[a]	0.005 (0.005)[a, b]	0.006 (0.006)[b]	0.02*
IMW	0.019 (0.010)[a]	0.008 (0.006)[b]	0.142 (0.012)[c]	<0.0001*
ICW	0.021 (0.007)[a]	0.011 (0.007)[a]	0.113 (0.018)[b]	<0.0001*

Abbreviations: ICW, intercanine width; IMW. intermolar width; MD. mesiodistal; OC, occlusocervical; SD, standard deviation.
[a, b, c]Different letters denote statistically significant differences.
*Statistically significant at $p < 0.05$.

Table 2 Comparison of IMW and ICW in study groups to reference casts

	Reference	Printed		Conventional		Digital	
	Mean (SD)	Mean (SD)	% of reference	Mean (SD)	% of reference	Mean (SD)	% of reference
IMW	47.78 (2.83)	47.79 (2.92)	0.02	47.78 (2.93)	–	47.92 (3.03)	0.29
ICW	29.16 (4.04)	29.18 (4.17)	0.07	29.17 (4.18)	0.03	29.27 (4.32)	0.38

Abbreviations: ICW, intercanine width; IMW. intermolar width; SD, standard deviation.

the two other groups (means= 0.019 and 0.008 in IMW and mean = 0.021 and 0.011 in ICW), $p < 0.0001$.

►**Table 2** shows that the mean (standard deviation [SD]) IMW and ICW in the reference casts were 47.78 (2.83) and 29.16 (4.04) mm. The conventional casts had the least error as percent of mean reference measurements followed by the printed casts (mean = 0.02% and 0.07%) and digital casts (mean = 0.29 and 0.38%).

Discussion

Dental stone cast is a cornerstone in prosthodontic diagnosis and treatment planning with long and proven history, but its associated drawbacks gave rise to digital alternatives. However, the digital cast has to be accurate to replace the stone cast and physical replication should be possible if needed.

In this study, the accuracy of SLA printed casts produced from 3Shape intraoral scanners showed minor error in comparison to conventional stone cast. These SLA printed casts and conventional stone casts exhibited greater accuracy than digital casts produced from the same intraoral scanner. These findings support the benefits of using printed casts in diagnosis, treatment planning, and fabrication of prosthetic restorations more than digital casts. Thus, the null hypothesis that there were no statistically significant differences between the accuracy of SLA casts and conventional stone casts was partly supported but the part of the hypothesis regarding the accuracy of SLA printed casts and digital casts was rejected as there was statistically significant difference.

Digital arch width (IMW and ICW) suffered the greatest error and it had a positive bias indicating that it was larger on the digital replicas. This also agrees with previous studies.[28-31] The cause of this error in the arch width measurements is due to overestimation of digital measurements in comparison to stone and printed casts. Also, distortion of arch happens during scanning of dental casts.[32] But this error is still within the acceptable clinical range which comes in agreement with other studies.[4,24,33] The same finding was described by Keating et al.[34] Thus, prototyped models are considered a valid alternative to stone models in term of prosthodontic treatment.[13,35,36]

This study used only one type of intraoral scanners and one type of 3D printers. Also, it is an in vitro study not simulating the conditions in the oral cavity, such as saliva, bleeding, limited mouth openings, and difficulty in vision, which are considered limitations of the current study. Thus, further studies are needed to evaluate the accuracy of other scanners and printers in comparison with the types used in this study. In addition, there is a need for future in vivo studies simulating oral conditions.

Conclusion

1. Rapid prototyped casts are valid alternative to digital and stone casts with clinically acceptable accuracy in terms of diagnosis, treatment planning, and fabrication of prosthetic restorations or appliances.
2. Although digital casts showed a positive bias in comparison to printed and conventional casts, the errors of digital casts are within acceptable clinical range.
3. Interarch width overestimation was greatest in digital models due to arch distortion during cast scanning procedure.

Conflict of Interest
None declared.

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