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JADA 2014;145(11):1133-1140
10.14219/jada.2014.87

ADA CE Program ARTICLE 3

Accuracy of computer-aided design/computer-aided manufacturing–generated dental casts based on intraoral scanner data

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ABSTRACT

Background. Little is known about the accuracy of physical dental casts that are based on three-dimensional (3D) data from an intraoral scanner (IOS). Thus, the authors conducted a study to evaluate the accuracy of full-arch stereolithographic (SLA) and milled casts obtained from scans of three IOSs.

Methods. The authors digitized a polyurethane model using a laboratory reference scanner and three IOSs. They sent the scans (n = five scans per IOS) to the manufacturers to produce five physical dental casts and scanned the casts with the reference scanner. Using 3D evaluation software, the authors superimposed the data sets and compared them.

Results. The mean trueness values of Lava Chairside Oral Scanner C.O.S. (3M ESPE, St. Paul, Minn.), CEREC AC with Bluecam (Sirona, Bensheim, Germany) and iTero (Align Technology, San Jose, Calif.) casts were 67.50 micrometers (95 percent confidence interval [CI], 63.43-71.56), 75.80 µm (95 percent CI, 71.74-79.87) and 98.23 µm (95 percent CI, 94.17-102.30), respectively, with a statistically significant difference among all of the scanners ($P < .05$). The mean precision values were 13.77 µm (95 percent CI, 2.76-24.79), 21.62 µm (95 percent CI, 10.60-32.63) and 48.83 µm (95 percent CI, 37.82-59.85), respectively, with statistically significant differences between CEREC AC with Bluecam and iTero casts, as well as between Lava Chairside Oral Scanner C.O.S. and iTero casts ($P < .05$).

Conclusion. All of the casts showed an acceptable level of accuracy; however, the SLA-based casts (CEREC AC with Bluecam and Lava Chairside Oral Scanner C.O.S.) seemed to be more accurate than milled casts (iTero).

Practical Implications. On the basis of the results of this investigation, the authors suggested that SLA technology was superior for the fabrication of dental casts. Nevertheless, all of the investigated casts showed clinically acceptable accuracy. Clinicians should keep in mind that the highest deviations might occur in the distal areas of the casts.

Key Words. Intraoral scanner; digital impression; milling; stereolithography; dental casts; accuracy; precision; trueness.

JADA 2014;145(11):1133-1140.

doi:10.14219/jada.2014.87

Plaster casts have been used as a standard of care for many years in diagnosis, treatment planning and fabrication of restorations. These casts, however, are subject to loss, fracture and degradation and require storage space.[1,2] To overcome these disadvantages, three-dimensional (3D) digital models obtained from intraoral scanners (IOS) can be used as an alternative to conventional casts. They can be stored easily, require little storage space and can be transmitted digitally,[3] and their use may increase productivity.[4,5] However, some cases, such as those involving complex prosthodontic treatment or removable restorations, still require physical dental casts. Several manufacturers provide physical dental casts based on IOS data sets using either stereolithography (SLA) (Sirona, Bensheim, Germany, and 3M ESPE, St. Paul, Minn.) or milling (Align Technology, San Jose, Calif.).

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Figure 1. Computer-aided design/computer-aided manufacturing–generated casts. **A.** Stereolithographic cast based on data from CEREC AC with Bluecam (Sirona, Bensheim, Germany). **B.** Stereolithographic cast based on data from Lava Chairside Oral Scanner C.O.S. (3M ESPE, St. Paul, Minn.). **C.** Milled cast based on data from iTero (Align Technology, San Jose, Calif.).

The fabrication technology involved in making these casts uses rapid prototyping. The term "rapid prototyping" describes a variety of processes for manufacturing 3D physical objects using 3D computational data and automated machines.[6-8] In general, it can be distinguished from subtractive and additive technologies. Subtractive technologies—such as computer numerical control machining, laser cutting, water jet cutting, electron beam cutting or electrical discharge machining—use computer-driven machines to cut away material when fabricating the predetermined computer-aided–designed (CAD) object.[9,10] In contrast, additive technologies—such as SLA, selective laser sintering, fused deposition modeling or 3D printing—are used to fabricate the objects by gradually adding materials.[11]

Although most IOS manufacturers offer fabrication of dental casts based on intraoral scan data, there is a lack of studies in which investigators evaluated the dimensional accuracy of these casts. Therefore, we conducted a study to investigate the accuracy, in terms of trueness and precision, of computer-aided design/computer-aided manufacturing (CAD/CAM) –generated casts based on the data of three IOSs.

METHODS

We used three IOSs (CEREC AC with Bluecam, CEREC 3D Service Pack V3.85, Sirona; Lava Chairside Oral Scanner C.O.S., Lava Software 3.0, 3M ESPE; iTero, Software Version 4.0, Align Technology), as well as a laboratory reference scanner (IScan D101, Imetric 3D, Courgenay, Switzerland; manufacturer's specifications: point spacing of 70 micrometers, noise level of 5 µm, repeatability level of ≤ 10 µm, accuracy of ≤ 20 µm) to digitize a full-arch polyurethane cast (Alpa-Pur, Shore A 70, CHT BEZEMA R. Beitlich, Tübingen, Germany) with 14 prepared abutments. First, we digitized the reference model by using the laboratory scanner. Then, one dentist who had received one week of training scanned the reference model with the IOSs (five scans per IOS). Subsequently, we sent the data sets obtained from the IOSs to the manufacturers to have them produce one physical cast per data set by means of SLA or milling (Figure 1). We obtained five physical casts per scanner to use in our evaluation.

Digitization of the reference models and the CAD/CAM-generated casts. To verify the reliability of the reference scanner, we scanned the reference model five times (R_1-R_5) before scanning the same model with the IOSs five times each and again with the reference scanner once after all of the IOS scans (R_6). To avoid contaminating and distorting the data sets due to the essential surface coating of CEREC AC with Bluecam and Lava Chairside Oral Scanner C.O.S., we performed all of the scans under the same conditions (temperature [standard deviation {SD}], 20.5 [1] °C; relative humidity [SD], 51 [2] percent) and followed a specific scanning order:

1. reference scanner (n = 5) (data sets R_1-R_5);
2. iTero (n = 5);
3. Lava Chairside Oral Scanner C.O.S. (n = 5), light coating (Lava Powder, 3M ESPE) and cleaning with a soft brush and air;
4. CEREC AC Bluecam (n = 5), coating (CEREC Optispray, Sirona Dental Systems) and cleaning with a soft brush and air;
5. reference scanner (n = 1) (data set R_6).

For Lava Chairside Oral Scanner C.O.S., the scanning process included a prescan calibration (Lava calibration tool, 3M ESPE), followed by using a zigzagwise scanning process and final recalibration.[12] We performed all other scans according to the manufacturers' instructions. Then we sent the data sets obtained from the three IOSs to the manufacturers to have them produce one physical cast per scan, thereby yielding five physical casts per IOS. After receiving the CAD/CAM-generated casts from the manufacturers, we scanned each cast three times with the reference scanner, resulting in 15 data sets per IOS:

ABBREVIATION KEY. CAD: Computer-aided design. **CAM:** Computer-aided manufacturing. **IOS:** Intraoral scanner. **SLA:** Stereolithographic. **UV:** Ultraviolet. **3D:** Three-dimensional.

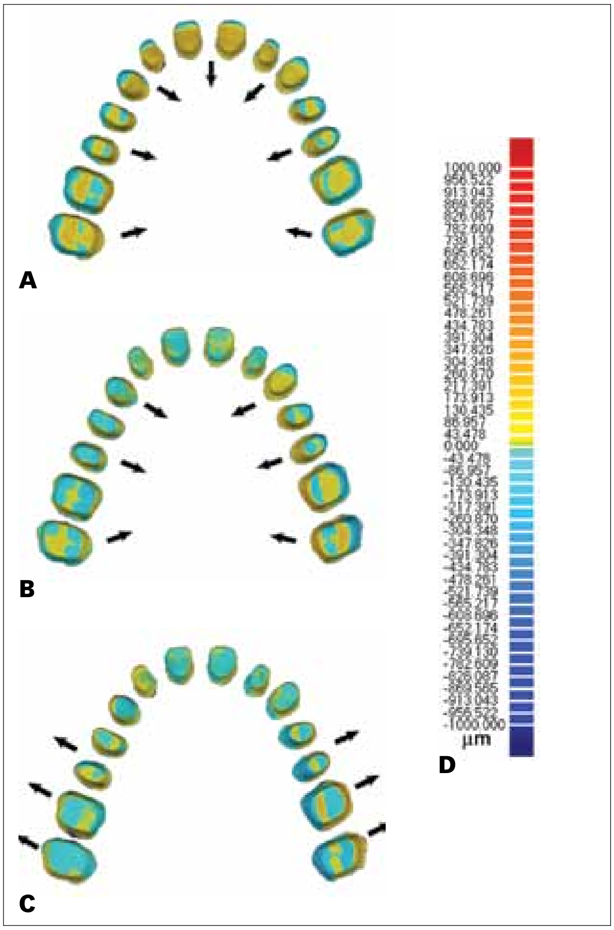

Figure 2. Color-coded images of the superimposed data sets. Data sets for CEREC AC with Bluecam (Sirona, Bensheim, Germany) (**A**) and Lava Chairside Oral Scanner C.O.S. (3M ESPE, St. Paul, Minn.) (**B**) show centripetal shrinkage. The data set for iTero (Align Technology, San Jose, Calif.) (**C**) shows a centrifugal expansion. Arrows indicate the direction of distortion. The color scale (**D**) explains the color-coded comparisons. µm: Micrometers.

6. iTero casts (C_1-C_5);
7. Lava Chairside Oral Scanner C.O.S. casts (C_6-C_{10});
8. CEREC AC with Bluecam casts (C_{11}-C_{15}).

3D evaluation of the data sets. We randomly selected one (R_1) of the five reference data sets (R_1-R_5) to obtain further trueness measurements, as well as to conduct the final evaluation of the reliability of the reference model. We imported the obtained files—the reference model data set (R_1) and data sets of the CAD/CAM-generated casts (C_1-C_{15})—into the 3D evaluation software (Geomagic Qualify 2012, Geomagic Solutions, Morrisville, N.C.). We removed artifacts that did not interfere with the actual abutment surface and cropped the visualized casts proximal to the preparation margin. We superimposed the R_1 and C_1-C_{15} data sets by using the software's best-fit algorithm and performed overall 3D comparisons. The software analyses results provided positive and negative deviations between the superimposed data sets.

We conducted further analyses by using the absolute values of the deviations, resulting in two values per evaluated cast and in a total of 30 values for the CAD/CAM-generated casts of each IOS. The accuracy of the physical casts was expressed in terms of trueness and precision.[13,14] We defined "trueness" as the comparison between a reference data set (R_1) and a test data set (C_1-C_{15}). We defined "precision" as a comparison among the various data sets obtained from the same object (that is, the physical casts C_1-C_{15}). Such an examination provided information about the repeatability of a scanner or scan.

Finally, we visually inspected the data sets and implemented statistical analyses.

Statistical analysis. Using the statistical software (SAS Version 9.1.2., PROC MIXED, SAS Institute, Cary, N.C.), an independent statistician (S.S.) fitted a one-way analysis of variance to compute absolute differences among the data sets of the CAD/CAM-generated casts (C_1-C_{15}; precision; n = 30 scans per IOS), as well as among the data sets of the CAD/CAM-generated casts (C_1-C_{15}) and the reference scan (R_1; trueness; n = 30 scans per IOS). To evaluate the effect of each of the evaluated casts, we evaluated the variation of measurements for each outcome by using a one-way repeated-measures analysis of variance design. We used the least-square method to calculate the means of both the main effects and relevant interaction effects (95 percent confidence intervals [CI]), as well as to perform several multiple comparisons of least square means. First, we conducted pairwise comparisons among the casts, which required a *P* value adjustment (Tukey-Kramer method). Second, we evaluated the comparisons of the casts per IOS, which also required a *P* value adjustment (Benjamini-Hochberg correction method). We set a level of statistical significance at $P < .05$.

RESULTS

The superimposition of the reference scanner data sets revealed no statistically significant differences among the data sets obtained before the IOS scans (R_1-R_5) or for the evaluation of the difference between R_1 and R_6. The absolute mean (SD) of the reference data sets was 3.3 (1.7) µm (R_1-R_5) and 1.5 (0.7) µm (R_1 and R_6).

The results of the visual analysis of the superimposed data sets (R_1; C_1-C_{15}) showed deviations in the horizontal and vertical planes of the data sets. Compared with the reference data set (R_1), the data sets of CEREC AC with Bluecam (C_{11}-C_{15}) and Lava Chairside Oral Scanner C.O.S. (C_6-C_{10}) revealed horizontal contractions and vertical distortion, whereas the data sets of iTero (C_1-C_5) showed mainly horizontal expansions located in the premolar and molar regions (Figure 2).

The absolute mean (SD) trueness of all of the scanned CAD/CAM-generated casts (C_1-C_{15}) was 80.51 (26.23) µm (n = 90). The absolute trueness values of the scanned

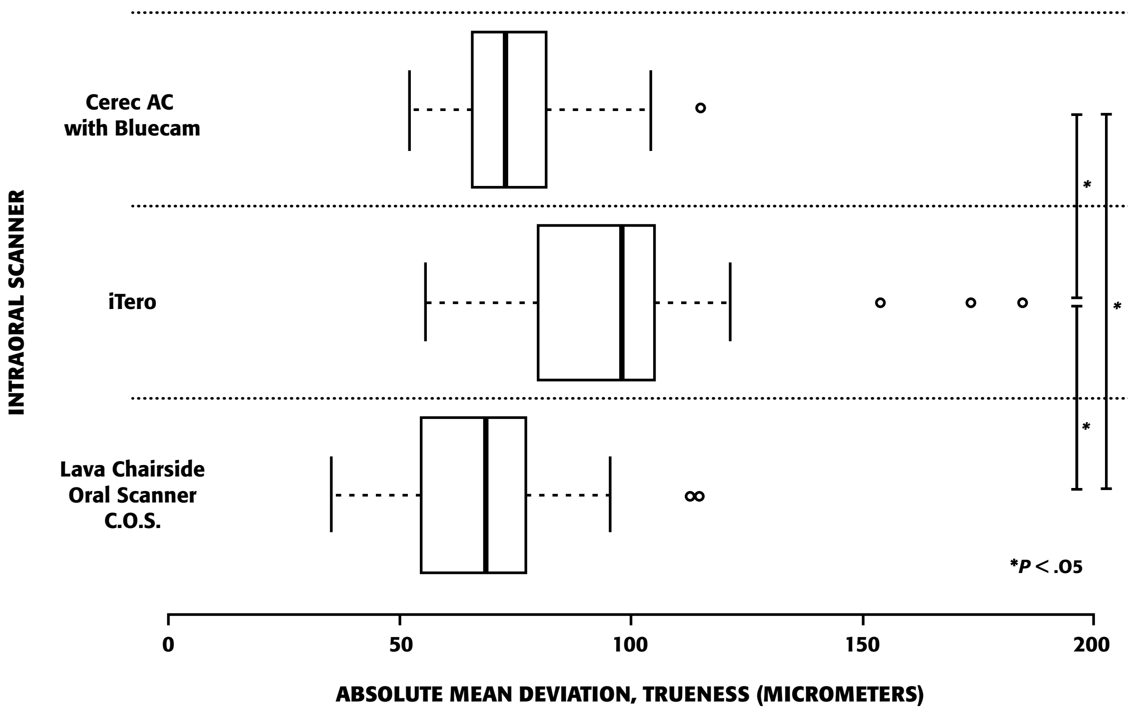

Figure 3. Overall absolute mean trueness values (95 percent confidence interval; $P < .05$) of the intraoral scanners. The brackets and asterisks indicate statistically significant differences. CEREC AC with Bluecam is manufactured by Sirona, Bensheim, Germany. iTero is manufactured by Align Technology, San Jose, Calif. Lava Chairside Oral Scanner C.O.S. is manufactured by 3M ESPE, St. Paul, Minn.

Lava Chairside Oral Scanner C.O.S. (C_6-C_{10}; n = 30), CEREC AC with Bluecam (C_{11}-C_{15}; n = 30) and iTero (C_1-C_5; n = 30) casts were 67.50 µm (95 percent CI, 63.43-71.56), 75.80 µm (95 percent CI, 71.74-79.87) and 98.23 µm (95 percent CI, 94.17-102.30), respectively. The results of data analysis showed statistically significant differences among all of the scanners ($P < .05$) (Figure 3).

The absolute mean (SD) precision of all of the scanned CAD/CAM-generated casts (C_1-C_{15}) was 28.07 (29.95) µm (n = 90). The absolute mean precision values for the scanned Lava Chairside Oral Scanner C.O.S. (C_6-C_{10}; n = 30), CEREC AC with Bluecam (C_{11}-C_{15}; n = 30) and iTero (C_1-C_5; n = 30) casts were 13.77 µm (95 percent CI, 2.76-24.79), 21.62 µm (95 percent CI, 10.60-32.63) and 48.83 µm (95 percent CI, 37.82-59.85), respectively. We found statistically significant differences between CEREC AC with Bluecam (C_{11}-C_{15}) and iTero (C_1-C_5) casts, as well as between Lava Chairside Oral Scanner C.O.S. (C_6-C_{10}) and iTero (C_1-C_5) casts ($P < .05$) (Figure 4).

DISCUSSION

The fabrication of dental casts on the basis of CAD/CAM technology includes several steps: data acquisition, data processing, manufacturing and postprocessing. As a consequence, each step may lead to inaccuracies or errors that can result in distortions of the final cast. A crucial factor is data acquisition by means of the IOSs.[15] Thus, inaccurate primary data sets might result in propagation error throughout the CAD/CAM process. The scanners use different technologies to capture the intraoral surfaces. CEREC AC with Bluecam and iTero are point-and-click IOSs, and Lava Chairside Oral Scanner C.O.S. is a video-based system.[16] Point-and-click IOSs require that there be at least a one-third overlap of adjacent surface scans to be able to perform a proper image stitching. A video-based system, however, takes a continuous stream of images (Lava Chairside Oral Scanner C.O.S. frame rate, 20 images/second) generating surface data with larger areas of overlapping. This feature might result in more accurate data sets, as reported previously.[15]

Lava Chairside Oral Scanner C.O.S. uses powder particles for the image registration process, and CEREC AC with Bluecam requires a surface-coating application of powder to avoid defuse reflections and to establish a uniform surface. Although the light dusting of powder used with Lava Chairside Oral Scanner C.O.S. seems to have not influenced the accuracy negatively, the powder used with CEREC AC with Bluecam might have affected the accuracy of the data sets negatively and, thus, the CAD/CAM-generated casts. However, no published reports exist regarding the influence of surface coating on the accuracy of the scan and, thus, on a fabricated CAD/CAM-based cast. In addition, intraoral scans obtained from a real clinical setting might be influenced by patients'

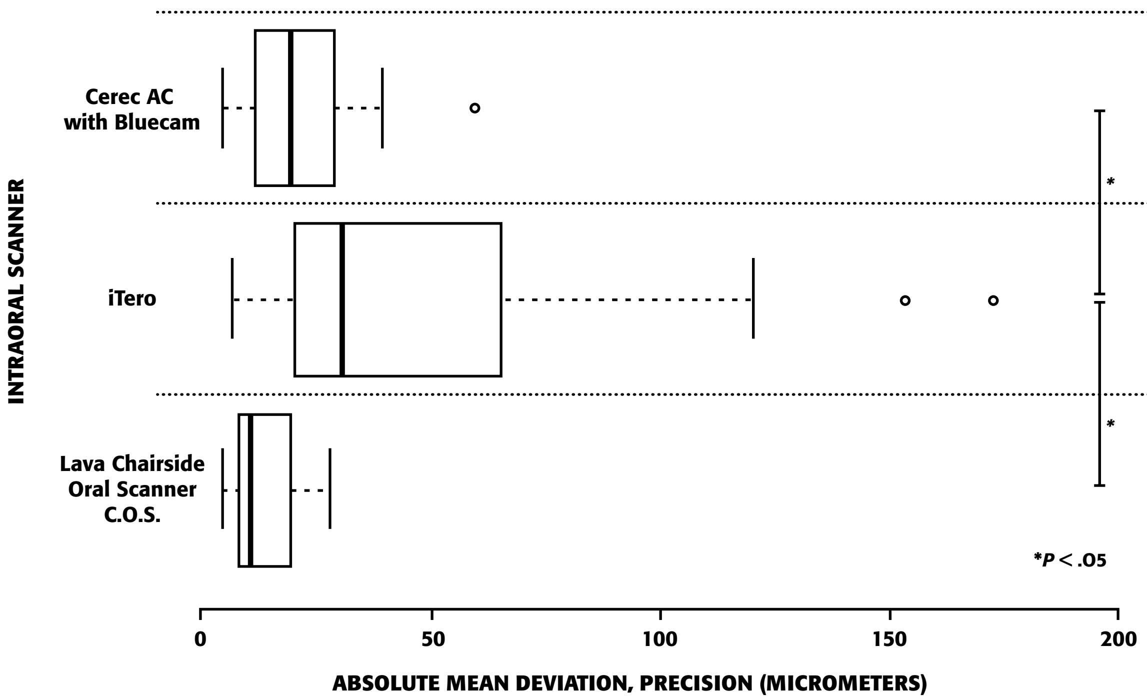

Figure 4. Overall absolute mean precision values (95 percent confidence interval; $P < .05$) of the intraoral scanners. The brackets and asterisks indicate statistically significant differences. CEREC AC with Bluecam is manufactured by Sirona, Bensheim, Germany. iTero is manufactured by Align Technology, San Jose, Calif. Lava Chairside Oral Scanner C.O.S. is manufactured by 3M ESPE, St. Paul, Minn.

movements or the presence of saliva or blood, which could alter the accuracy of a CAD/CAM-generated cast.

In addition to the initial data acquisition step, the data processing step might have influenced the accuracy of the IOSs. During the process of preparing the data to generate a physical cast, creating slices of the 3D data set is necessary. During this process, errors associated with tessellation and cusp height errors may occur. Cusp height is a quantification of the "stair-step" effect achieved in rapid prototyping. Cusp height represents the distance between the intended and the approximated surface and gives information about the surface accuracy.[17] Tessellation is the process of approximating a surface using triangles and is inherent to SLA. The number and size of the triangles depends on the number of points and the point-to-point distance (point spacing) of the point cloud of the captured surface primarily generated by means of a 3D scanner. Consequently, the more points that are available, the smaller the distances between the points and thus more triangles that are available for the surface reconstruction. This results in a more detailed data set, as well as a large amount of data. However, it is not possible to increase the number of points in the point cloud ad infinitum, because tessellation is limited by the capabilities of the applied hardware.[18] We did not obtain information from the manufacturers about the number of points and the point spacing used by the IOSs in our study. Nevertheless, the previously described aspects might be an explanation for the differences between casts generated by means of Lava Chairside Oral Scanner C.O.S. and CEREC AC with Bluecam, both of which use the same technology for the fabrication of CAD/CAM-generated casts.

SLA (CEREC AC with Bluecam and Lava Chairside Oral Scanner C.O.S.) and milling (iTero) are two technologies that can be used to produce physical objects. Owing to the manufacturers' proprietary policies, we were not able to obtain any specific information about the materials or techniques (for example, resin type, laser type, layer thickness, laser spot size, cutting tools) used for fabricating the casts. Therefore, we are limited in our ability to describe potential general issues that may occur during milling or SLA.

There is a lack of literature in which investigators studied the dimensional accuracy of CAD/CAM-generated casts by using subtractive technology such as milling. Schmitz and colleagues[19] reported the following factors that potentially could influence dimensional accuracy:

- thermal errors caused by thermal expansion or contraction of the machine structure or cutting tools;
- vibration errors caused by tool chattering or dynamic excitation of the machine;
- tool deflection errors caused by deflecting or bending the static milling tools owing to machining forces.

In general, tools are subject to wear, resulting in a loss of length and diameter and, thus, a reduction of the machined surface over time. Furthermore, elastic recovery also can be considered a significant source of error in the milling process. During the milling process, the cutting tool is pressed on the machined object, pushing it in the direction of the highest force. When the force is removed, the cutting tool, the machined object or both act like an elastic spring "bouncing back" to the original position.[19] In addition, the shape and size of the bur might be a limiting factor when it comes to the milling of detailed structures. The smallest possible geometric shape that can be milled corresponds directly with the shape of the tip of the bur and of the ability of the machine to rotate the object to be milled.

SLA, which was invented by Charles Hull in 1983,[20] is performed by consecutively polymerizing layers of a light-curable material (photopolymer). Basically, a laser beam of ultraviolet (UV) light that is focused on a liquid photopolymer draws contours of an object on the surface of the liquid, polymerizing or crosslinking a thin layer of the polymer. Then the polymerized object is immersed a defined depth into the liquid, allowing the photopolymer to cover the object, and the laser beam polymerizes a new layer. By repeating the aforementioned steps, the process creates a 3D object, layer by layer.[18,20]

Besides the photopolymer, several process-related factors might influence the final accuracy of the casts. These factors include the thickness of the layer of the polymerized material, the degree of polymerization shrinkage, the amount of overcuring or the properties of the laser beam (for example, the size of laser spot and the exposure rate). A fundamental factor in the surface structure of an SLA-generated object is the thickness of the layer. The layer-by-layer buildup technique creates a stair-step effect of the object's surface.[21] Depending on the thickness of the layer, the object surface is either more or less smooth and detailed. The stair-step effect could be caused by the geometric approximation of a curved surface resulting from the building up of layers of uniform thickness, material shrinkage of layers during the process or the angle and extinction of the laser beam. The stair-step effect might result in dimensional errors and a rough surface.[22] In addition, the thickness of the layer may influence the overall strength of an SLA-generated object. A layer thickness of 125 µm or greater leads to low residual stress and strain relief in the fabricated object.[23]

Photopolymerization, which typically is accompanied by material shrinkage, can cause residual stress, skewing or distortion of an SLA-generated object. Two types of dimensional distortions can occur: cure-related shrinkage and thermal expansion or contraction. Cure-related shrinkage is caused by changes in the chemical bond distances of the nonpolymerized monomer compared with those of the polymer (6-10 percent possible shrinkage), whereas thermal expansion or contraction occurs when the temperature changes in the resin during the exothermic polymerization.[24-26]

Laser overcuring bonds layers to each other. Although it is a necessary part of the process of creating a solid object, it may cause dimensional and positional errors in the object's z direction, resulting in a deformed shape and a shift of the object's center position.[18] Finally, postcuring (by means of UV light and heat) of SLA-generated objects is necessary to solidify unreacted or partially reacted monomers, thus increasing the mechanical properties of the SLA-generated objects. This process of additional polymerization may result in shrinkage or warping. This sensitivity to UV light, heat and oxygen requires special storage modalities and protection of the final SLA-generated objects to prevent them from cracking, losing their gloss, chalking, experiencing pigment fading, delaminating or peeling and corroding. To ensure that no adverse effects would occur, we stored the SLA-generated casts in UV light–protected paper boxes until the casts could be digitized with the reference scanner within one week of receipt from the manufacturer.

CAD/CAM-generated models are used to replace conventionally produced stone casts and require accuracy that is at least as good as that of stone casts. Ender and Mehl[27] reported that stone casts had precision and trueness values (SD) of 12.5 (2.5) µm and 20.4 (2.2) µm, respectively. In our study, only Lava Chairside Oral Scanner C.O.S.–based casts had comparable precision values.

For iTero casts, most deviations were visible in the posterior areas, indicating a centrifugal expansion (Figure 2). This corresponds with findings of a 2013 study in which investigators studied the accuracy of the primary data sets of IOSs.[15] The authors reported trueness values for full-arch scans based on data obtained from Lava Chairside Oral Scanner C.O.S., iTero and CEREC AC Bluecam of 38 µm, 49 µm and 332.9 µm, respectively, and precision values of 38 µm, 40 µm and 99 µm, respectively. The deviations likely were caused by a summation of errors during scanning and data processing (that is, stitching together the individual images).[28,29] This summation of errors can lead to a distally expanded and slightly twisted final cast. On the other hand, the visual evaluation of the CAD/CAM-generated casts based on Lava Chairside Oral Scanner C.O.S. and CEREC AC with Bluecam data sets revealed a centrifugal shrinkage possibly caused by the previously mentioned manufacturing-related issues.

In our study, we found that SLA-generated casts had a higher accuracy than did milled casts. A comparison of our findings with those of previous studies was not possible, owing to the fact that no studies regarding 3D evaluation of the accuracy of full-arch CAD/CAM-generated casts are available. We noted that investigators in most of the studies we found in the literature obtained linear measurements and compared the values of manual stone cast measurements (that is, measurements performed by means of calipers) with measurements obtained from digital models.[30-45] Additional articles in which investigators made comparisons focused on the accuracy of impressions[12,46] or evaluated the fit of the final restoration.[47,48] Hwang and colleagues[32] reported results about milled models similar to those in our study. They compared the accuracy (vertical and horizontal linear measurements) of stone casts with three types of casts (digital, milled polyurethane and acrylic rapid prototyping) based on intraoral data from the iTero scanner. The milled polyurethane models showed the least accuracy, with a mean error of 1.5 millimeters compared with stone and digital casts. However, these models used a stone cast as reference model, allowing for the potential risk of distortions caused by water uptake and mechanical irritations. Likewise, Kim and colleagues[49] reported a discrepancy of milled polyurethane models when compared with stone casts of a first molar in vitro impression generated by either iTero data sets or conventional impression material.

One limitation of our study was the lack of a comparison of the CAD/CAM-generated casts with conventional stone casts. The intention of our investigation, however, was to compare the overall accuracy of CAD/CAM-generated casts based on data from different IOSs and their manufacturing technologies with that of a reference model. For a more comprehensive overview, investigators in future studies might use a study design that also includes an evaluation of stone casts.

Although we were able to identify differences among the technologies used to fabricate the physical CAD/CAM-generated casts, we noted that all of the casts had a clinically acceptable level of overall accuracy. SLA manufacturing technology, however, seemed to have had a higher level of accuracy than did milling. Nevertheless, it was not only the manufacturing process (SLA or milling) that influenced the final accuracy of a CAD/CAM-generated cast, but also the entire process, starting with the intraoral scan and concluding with how the cast was stored.

CONCLUSIONS

All of the casts had a clinically acceptable level of accuracy; however, SLA manufacturing technology (CEREC AC with Bluecam and Lava Chairside Oral Scanner C.O.S.) seemed to have a higher level of accuracy than did milling (iTero). Clinicians should keep in mind the potential risk of distortions in casts, especially in the posterior areas of CAD/CAM-generated casts. ■

Disclosure. None of the authors reported any disclosures.

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