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RESEARCH AND EDUCATION

Positional trueness of three removable die designs with different root geometries manufactured using stereolithographic 3D printing

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ABSTRACT

Statement of problem. Three-dimensional (3D) printed casts are a suitable alternative to dental stone casts. Contemporary dental design computer programs permit designing definitive casts with removable dies with different root geometries and retention mechanisms. Studies on the positional trueness of 3D-printed removable dies with different root geometries are lacking.

Purpose. The purpose of this in vitro study was to investigate the 3D displacements of three 3D-printed removable die designs with different root geometries.

Material and methods. The digital file of a dental stone alveolar cast with root-form removable dies (MOD UJ IV Fixed Prosthetics; Ivoclar AG) was used as a reference to create 3 removable die and alveolar cast designs (Root Form, RF; Conical, CON; Cylindric, CYL) with different root geometries in 2 dental design computer programs (DentalCAD 3.1 Rijeka; exocad; GmbH; InLab CAD 22.0; Dentsply Sirona). 3 equidistant Ø1-mm spheres (C, Cervical; M, Middle; O, Occlusal) were designed on the buccal surface of the coronal portion of the removable die to evaluate their displacement. A total of 45 alveolar casts with 45 removable dies were fabricated using a stereolithographic 3D printer (Form 3; Formlabs); each die group consisted of 15 specimens. After fabrication and postprocessing, the specimens were scanned, and their digital files were analyzed in a metrology-grade computer program to evaluate the displacement of the removable dies with respect to the position of the die in the master reference file. Subsequently, the data were analyzed using a 3-way analysis of variance (ANOVA) followed by step-down Bonferroni-corrected pairwise comparisons (α=.05).

Results. Two statistically significant 2-way interactions were detected between the independent variables, die design and direction (P<.001), and location and direction (P<.001). The post hoc analysis identified significant differences between the displacement values of RF and CYL (P<.001) and RF and the CON (P<.001) designs on the Y axis. The measured displacements were statistically different between the C and O locations on the Y axis (P=.001) and the M and O locations on the Z axis (P=.006).

Conclusions. The root geometry of a 3D-printed removable die and alveolar cast can affect seating, and variable degrees of tipping of the removable die can be seen. The seating and congruence of the removable die with the interocclusal space and relationships observed intraorally should be confirmed before adjusting indirect restorations. (J Prosthet Dent xxxx;xxx:xxx-xxx)

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Clinical Implications

The geometric features of the root portions of the 3D printed alveolar cast and removable die may affect the seating of the die, leading to vertical displacement and buccolingual tipping. A careful inspection of the root portions of the removable die and alveolar cast, the interocclusal space available, and the relationship with the adjacent teeth should be conducted before adjusting indirect restorations. Clinicians may consider making an elastomeric occlusal registration to validate the interocclusal relationship and seating.

Removable dies must accurately reproduce the position, surface area, and margins of the prepared teeth to permit the accurate fabrication of indirect restorations.[1] Various types of removable dies have been suggested for specific clinical situations, and materials such as dental stone, epoxy resin, and acrylic resin have been successfully used as removable die materials,[2] the most common being dental stone. Traditionally, removable dies consist of a dental stone replica of the tooth preparation with a metal dowel pin that allows its repositioning at the base of the cast.[3] An alternative removable die design consists of fabricating single-piece dental stone dies with tapered apical extensions with axial grooves that guide insertion and removal from a solid cast with a socket-shaped space.[1] Regardless of the technique, fabricating accurate removable dies involves multiple technique-sensitive laboratory steps that demand a high level of expertise to ensure accuracy and minimal displacement.[1,3]

Three-dimensional (3D) printing has been used in dentistry to create appliances such as fixed partial dentures, surgical guides, maxillofacial prostheses, and alveolar casts with removable dies.[4–6] Research suggests that 3D printed casts fabricated with different additive manufacturing technologies, including digital light projection and stereolithography (SLA), provide clinically acceptable accuracy[7–9] and can be used for the fabrication and adjustment of definitive dental prostheses.[6,8,10,11] However, factors such as layer thickness,[12] printing orientation,[13] base design,[14] postprocessing protocols, temperature,[15] storage conditions, and the 3D manufacturing trinomial (3D printer, technology, material)[16] can affect the accuracy and surface features of the manufactured objects.[5,10,17] Recently, clinically relevant factors such as the error propagation of digital scans to 3D printed casts,[18] the accuracy and trueness of complete arch intraoral scans,[19–22] and the effect of different manufacturing parameters on the accuracy of 3D printed casts and removable dies have been evaluated.[9,12] Although research has demonstrated that contemporary 3D printers are highly accurate,[5] when the design comprises multiple components, as for the alveolar casts with removable dies used to fabricate fixed partial dentures, factors such as layer thickness and the geometry of the retentive portion can affect the fit between the removable die and the cast.[12] Research suggests that even slight discrepancies in the relationships between the removable die and its cast can compromise the contours of indirect restorations and the accuracy of the adjustments performed using traditional methods such as selective grinding guided by articulating paper markings.[23] Therefore, defining which 3D-printed removable die designs provide satisfactory positional trueness is necessary to fabricate appliances that closely replicate the intraoral situation. The authors are unaware of research describing the positional trueness of 3D printed dies with different root geometries.

The present study evaluated the 3D displacements of 3 removable die designs with different root geometries manufactured through SLA 3D printing. The null hypotheses were that the removable die design, the location used for the measurements, and the direction of the movement on the X, Y, and Z axes would not affect the mean displacements of the different removable dies.

MATERIAL AND METHODS

The 3D displacements of three 3D printed removable die designs were assessed with a metrology-grade computer program (Geomagic Control X; 3D Systems). A pilot study was performed, and a sample of 15 was estimated by using a statistical power calculation computer program (G*Power; Heinrich-Heine-Universität Düsseldorf) to provide a statistical power of 80%. An effect size of 1.19 and a sensitivity of 0.04 mm were used for this calculation; the 0.04-mm thickness corresponded to the thickness of an articulating paper recommended to adjust indirect restorations.[23]

The posterior left sextant of a maxillary dental stone cast (MOD UJ IV Fixed Prosthetics; Ivoclar AG) was scanned, and a standard tessellation language (STL) file was generated. Using an open-source 3D modeling computer program (Meshmixer; AutoCAD), the STL file of the dental stone cast was analyzed for errors and used to create a master reference file. The master reference file included the maxillary right first molar tooth preparation, its adjacent teeth, and surrounding tissues. The master reference file was oriented to the world origin with the Y+ axis up, the X+ axis to the distal, and the Z+ axis towards the lingual of the tooth preparation. In addition, 3 equidistant Ø1-mm spheres were designed on the buccal surface of the maxillary first molar: one located on the occlusal third (O), one in the middle third (M), and one in the cervical (C) third of the tooth preparation (Fig. 1). Subsequently, the master reference file was imported into a dental CAD computer program (InLab CAD 22.0; Dentsply Sirona) to design the Root-Form (RF) and Conical (CON) removable dies and

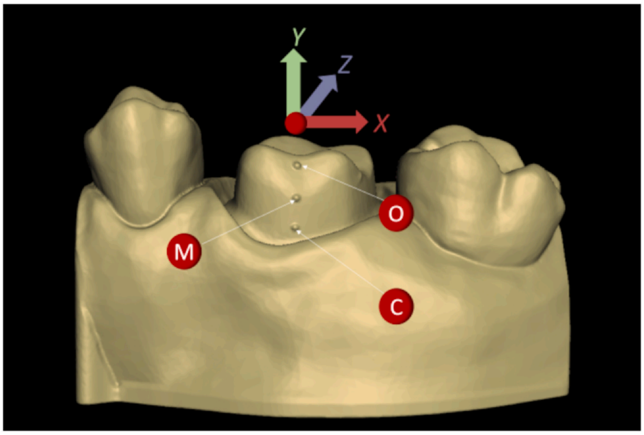

Figure 1. Master reference file with 3 equidistant Ø1-mm spheres on buccal surface.

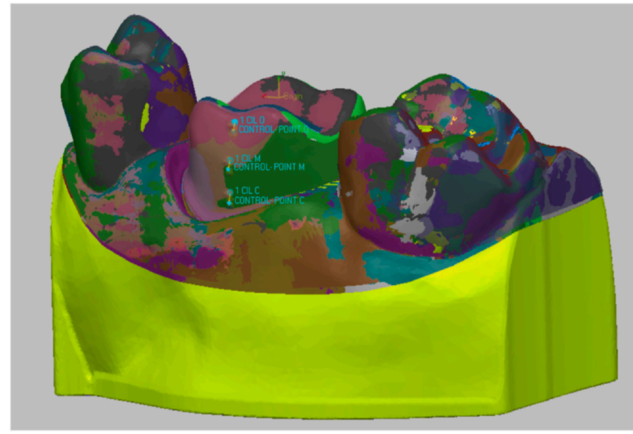

Figure 3. Analysis of positional trueness using constructed reference data points in metrology-grade computer program.

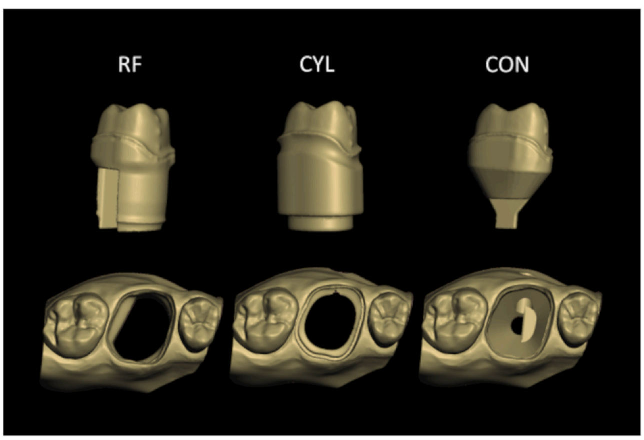

Figure 2. Removable die digital designs. CON, conical; CYL, cylindric; RF, root form.

alveolar casts. A third design, Cylindric (CYL), was created in a different dental CAD computer program (DentalCAD 3.1 Rijeka; Exocad; GmbH). The RF and CYL designs were generated using the following design parameters: 0.06-mm spacer, a circumferential ditch size of 0.75 mm, and an apical window. The CYL design was created using similar design parameters in the second dental CAD computer program (Fig. 2).

A total of 45 specimens consisting of 3D-printed alveolar casts with removable dies were manufactured in an SLA 3D printer (Form3; Formlabs) using a photopolymer formulated for manufacturing dental casts (Model Resin V2; Formlabs). Fifteen specimens were fabricated for each alveolar cast and removable die design with a layer thickness of 25 µm and 0-degree build orientation. Subsequently, all specimens were cleaned with 99% isopropyl alcohol (Commercial Alcohols; Greenfiled Global) and post-polymerized (FormCure; Formlabs) by following the manufacturer's recommendations.

After manufacturing, the specimens were scanned by the same operator (F.A.F.), who recorded the coronal portion of the removable die and the 3 equidistant spheres on the buccal surface. Additionally, the adjacent tissues and teeth were registered. Subsequently, the STL files were imported into a metrology-grade computer program (Geomagic Control X; 3D Systems). The coronal portion of the removable die of the master reference file was isolated from the rest of the scan using the Split/Region function, and the STL files of the specimens were aligned with the master reference file using the best-fit alignment function of the computer program by using the occlusal anatomy of adjacent teeth and surrounding tissues as landmarks. Subsequently, constructed reference data points were created on the surface of spheres located at the C, M, and O locations. The position of 3 locations on the X, Y, and Z axes was subtracted from the original coordinates of the master reference file to evaluate the displacement of the measured locations in each direction (Fig. 3).

The data were analyzed with a 3-way analysis of variance (ANOVA) (α=.05) to determine the effect and interaction of independent variables (die design, location, and direction) on the outcome variable (displacement). Additionally, step-down Bonferroni-corrected pairwise comparisons were conducted post hoc (α=.05).

RESULTS

The direction of 3D displacement of different locations of removable dies on the X, Y, and Z axes is displayed in Figure 4. The ANOVA detected 2 statistically significant 2-way interactions, one between the different removable die designs and the direction of their displacement (die design and direction) (F<.001) and the other between the measured locations and their displacement (location and direction) (F=.001) (Table 1). Therefore, to elucidate what affected the direction of the displacement of the

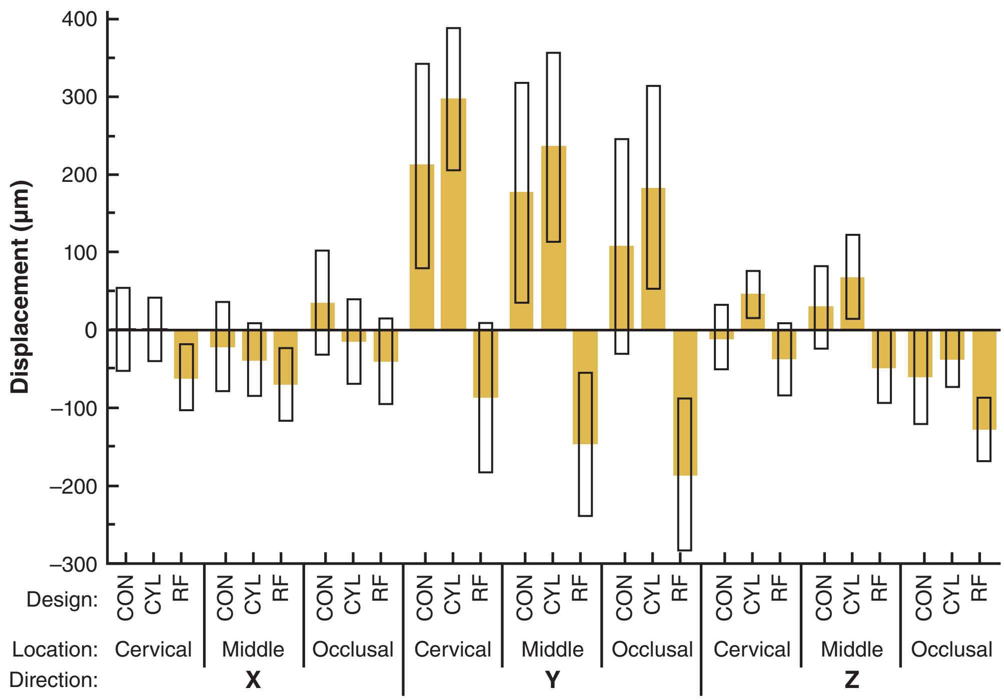

Figure 4. Displacement of different locations of removable dies on x, y, and z axes.

Table 1. Summary of results of three-way ANOVA

Effect	Num DF	Den DF	*F* Ratio	*P*
Die design	2	42	18.54	<.001
Location	2	336	7.05	.001
Die design × Location	4	336	0.21	.933
Direction	2	336	35.66	<.001
Die design × Direction	4	336	27.26	<.001*
Location × Direction	4	336	4.62	.001*
Die design × Location × Direction	8	336	0.14	.997

* Statistically significant at *P*<.05.

Table 2. Stepdown Bonferroni-corrected pairwise comparisons assessing different groups and direction of displacement

Die Design	Direction	Die Design	Estimate	*P*
CON	X	RF	0.062	.856
CYL	X	CON	-0.022	1
CYL	X	RF	0.039	1
CYL	Y	RF	0.377	<.001*
CON	Y	RF	0.305	<.001*
CYL	Y	CON	0.072	.515
CYL	Z	RF	0.096	.137
CON	Z	RF	0.057	.954
CYL	Z	CON	0.038	1

CON, Conical; CYL, Cylindrical; RF, Root Form.
* Statistically significant at *P*<.05.

Table 3. Stepdown Bonferroni-corrected pairwise comparisons for different locations and direction of displacement

Location	Direction	Location	Estimate	*P*
C	X	M	0.023	1
C	X	O	0.013	1
M	X	O	-0.036	1
C	Y	O	0.105	.001*
M	Y	O	0.053	.486
C	Y	M	0.051	.515
M	Z	O	0.092	.006*
C	Z	O	0.074	.062
C	Z	M	-0.017	1

C, Cervical; M, Middle; O, Occlusal.
* Statistically significant at *P*<.05.

different removable die designs, the location used for the measurements had to be considered. The results of the step-down Bonferroni-corrected pairwise comparisons are presented in Table 2.

A statistically significant difference was detected for the displacements on the Y axis between the RF and both the CYL and the CON removable die designs ($P<.001$). Additionally, when the direction of displacement between locations was assessed, a statistically significant difference was noted on the displacement of C and O locations on the Y axis ($P=.001$), and between O and M locations on the Z axis ($P=.006$) (Table 3).

DISCUSSION

The null hypotheses that the removable die design, the location used for the measurements, and the direction of the movement on the X, Y, and Z axes would not affect the mean displacements of the different removable dies were rejected, as the effect of two 2-way interactions was significant on the displacements measured. The interaction between the direction and design and the location and direction influenced the displacement of the removable dies (*P*<.05).

In the present study, the removable die designs displayed variable degrees of displacement on the X, Y, and Z axes. When the displacements of the CYL and RF designs on the X axis were assessed, mostly negative or low values were observed at the 3 measured locations, suggesting a modest mesial displacement. The O location in the CON design displayed positive displacements of 35 µm, suggesting tipping of the removable die towards the distal. All designs presented displacements on the Y axis; the largest displacements were observed on the CYL design, ranging from 183 µm to 296 µm depending on the location measured. Similarly, all the locations on the CON designs presented positive displacements, indicating incomplete seating of the removable die on the 3D printed alveolar cast. On the contrary, the RF designs displayed negative values ranging from −86 to −184 µm on all measured locations, suggesting vertical displacement in the apical direction. Additionally, the RF design displayed negative displacements on the Z axis, indicative of buccal displacement. Contrarily, the CYL removable dies presented mostly positive displacements on their C and M locations, while the O location displayed negative displacements (−37 µm), indicating a modest buccal tipping. Interestingly, the C and O locations of the CON group exhibited negative displacements on the Z axis, indicative of tipping towards the buccal.

The statistical 2-way interactions detected by the ANOVA helped elucidate the significant vertical displacement (*P*<.001) and positional deviation on the Z axis (*P*<.05) displayed by the different removable die designs. The large displacements on the Y axis suggest inadequate seating for both CYL and CON designs, which could lead to definitive restorations with inadequate occlusal contacts and deficient occlusal morphology. Vertical displacements of such magnitude could complicate corroborating the occlusion of the restorations with articulating paper,[23] which could lead to over-adjusting the restorations, inadvertently decreasing the magnitude and strength of the occlusal contacts. On the contrary, the apical displacement observed in the RF design could lead to restorations that would require the addition of material to develop the occlusal contacts; this could fracture during parafunctional episodes or if the underlying structure did not support the material properly.[3] In addition, if the occlusal contacts were built with inaccurate interocclusal relationships, this could lead to traumatic occlusion in the form of unwanted contacts during centric closure and eccentric movements.

Traditionally, removable dies are made with the same material as the alveolar cast.[1] Contemporary dental stone formulations provide excellent dimensional stability, fine surface detail reproduction, and 100% conversion at room temperature.[3] Conversely, 3D-printed objects experience material-specific limitations of 3D-printed photopolymers such as variable degrees of conversion, delamination, and polymerization shrinkage.[8,15] These deficiencies can affect the trueness of the printed object and compromise the seating of a removable die on the alveolar cast. Furthermore, manufacturing-related factors such as the staircase effect, orientation, and layer thickness can affect the trueness of 3D-printed dental appliances with complex geometries and intricate surface details.[5,12] Additionally, microscopic remnants of support insertions and resin residues present on critical segments of the root portion of the objects after manufacturing can compromise the seating of the removable die, thus compromising the accuracy of the removable die-alveolar cast complex.

In the present study, the complex geometric features of the root space of the alveolar casts were generated by the CAD computer program with predefined parameters. These features are meant to provide retention, stability, and support to the removable dies; therefore, their distortion would lead to tipping of the removable die towards the side where the geometry of the root space of the cast did not provide horizontal stabilization; in this study, the buccolingual direction, Therefore, the accuracy of these features should be verified immediately after manufacture, and the occlusal clearance and relationships observed in the 3D printed casts and removable die should be corroborated with those observed intraorally before using them to adjust indirect restorations. Verification can be achieved with intraoral photographs from different angles by means of visual inspection with a periodontal probe or with an intraoral occlusal registration, which could be repositioned on the removable die and cross-sectioned to reveal partial seating, horizontal displacements, and interocclusal space discrepancies.

Limitations of the present study include the use of a single photopolymerizable resin and 3D printer and the different CAD computer programs used to design the removable dies and alveolar casts. Even though the effect of the computer program would be expected to be minor, the authors acknowledge that the mesh geometries of the different removable die and alveolar cast designs may differ depending on the computing processes involved in their generation and can vary from one program to another. Additionally, the present study was conducted under specific experimental settings; therefore, different results may be obtained if different 3D manufacturing trinomials,[16] scanning technologies,[19–22] metrology software with a distinct superimposition algorithm, postprocessing, and storage conditions were used.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. Notable positive and negative displacements were noticed on the Y axis, suggesting seating inconsistencies or apical movement that varied depending on the root geometry of the removable dies.
2. Modest but significant displacements were detected on the Z axis, suggesting tipping of the removable dies in the buccolingual direction.
3. Care should be taken when adjusting indirect restorations on 3D-printed alveolar casts with removable dies. Validating their correspondence with the intraoral scenario by means of intraoral photographs, clinical measurements, occlusal registrations, and a meticulous visual inspection is recommended before adjusting or manufacturing indirect restorations.

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