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RESEARCH AND EDUCATION

Dimensional stability and fit of additively manufactured removable dies in dental cast resins with different chemical compositions

Fiona Cornelia Arnold, Med dent,[a] Mustafa Borga Dönmez, DDS, PhD,[b]
Hanan Al-Johani, BDS, MSD, PG Cert, PhD,[c] Çiğdem Kahveci, DDS, PhD,[d]
Martin Schimmel, Prof Dr med dent,[e] Burak Yilmaz, Prof Dr, DDS, PhD,[f] and Gülce Çakmak, DDS, PhD[g]

ABSTRACT

Statement of problem. Additive manufacturing has enabled the fabrication of removable dies in various resins with different compositions. However, the knowledge on the dimensional stability and fit of removable dies fabricated with different dental cast resins is lacking.

Purpose. The purpose of this in vitro study was to evaluate the effect of dental cast resin type and storage time on the dimensional stability and fit of AM removable dies throughout a 4-week period.

Material and methods. A typodont model with a prepared right first mandibular molar was digitized with an intraoral scanner (IOS) (CEREC Primescan) to generate a standard tessellation language (STL) file. The STL file was imported into a dental design software program to design a removable die with 10-degree shaft taper angle and a hollow partial arch cast with and without the die. The removable die and hollow partial arch cast without the die STLs were used to additively manufacture 48 removable dies (n=16) and 3 hollow casts (n=1) by using a dental cast resin (DentaMODEL) (AM-DM), a bio-based dental cast resin (FotoDent biobased model) (AM-FD), and a nanographene-reinforced dental cast resin (G-Print) (AM-GP). The same IOS was used to digitize each die and when the die was seated into its respective hollow cast 1 day (T0), 1 week (T1), 2 weeks (T2), 3 weeks (T3), and 4 weeks (T4) after fabrication. All STL files were imported into a metrology-grade 3-dimensional analysis software program (Geomagic Control X). The root mean square (RMS) was used to assess deviations in different die regions (crown, root, base of the root, and overall) over 4 weeks, along with fit evaluation by calculating RMS for the crown portion within the cast and measuring mean distance deviations at 5 points on the die. The generalized linear model analysis and Bonferroni-corrected post hoc tests were used to evaluate the data (α=.05).

Results. The dimensional stability of the removable dies was affected by the interaction between resin type and die region and by the interaction between the resin type and time point, while the fit of the dies was impacted by the interaction between resin type and time point (P<.001). AM-GP dies mostly had higher crown RMS than AM-FD dies (P<.001), while AM-DM dies had the highest root and base of the root RMS ($P\leq$.027). AM-FD dies had the lowest overall RMS ($P\leq$.038). The base of the root led to the highest RMS for each resin (P<.001). AM-FD dies had lower RMS than AM-GP at T0 and AM-DM at T2, while AM-GP dies had lower RMS than AM-DM at T1 ($P\leq$.010). The RMS values of AM-GP dies were lower at T1 than at T0 and T3 (P<.001). When the fit of the dies was considered, AM-FD dies had the lowest and AM-DM dies had the highest crown portion RMS and point-based deviations at each time point (P<.001). In addition, AM-DM dies' RMS values and deviations were the lowest at T0, while AM-FD dies had the highest point-based deviations at T4 ($P\leq$.034).

Conclusions. Within tested regions and time points, AM-FD dies mostly had higher dimensional stability and better fit. Therefore, the crowns to be adjusted on AM-FD dies may require fewer interproximal and occlusal adjustments. (J Prosthet Dent 2025;133:1520.e1-e10)

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[a]Dissertation student, Department of Reconstructive Dentistry and Gerodontology, School of Dental Medicine, University of Bern, Bern, Switzerland.
[b]Associate Professor, Department of Prosthodontics, Faculty of Dentistry, Biruni University, Istanbul, Turkey; and PhD student, Department of Reconstructive Dentistry and Gerodontology, School of Dental Medicine, University of Bern, Bern, Switzerland.
[c]Assistant Professor, Department of Restorative Dentistry, Faculty of Dentistry, King Abdulaziz University, Jeddah, Saudi Arabia.
[d]Private practice, Ordu Oral and Dental Health Center, Ordu, Turkey.
[e]Head of Department, Department of Reconstructive Dentistry and Gerodontology, School of Dental Medicine, University of Bern, Bern, Switzerland; and External Researcher, Division of Gerodontology and Removable Prosthodontics, University Clinics of Dental Medicine, University of Geneva, Geneva, Switzerland.
[f]Professor, Department of Reconstructive Dentistry and Gerodontology, School of Dental Medicine, University of Bern, Bern, Switzerland; Professor, Department of Restorative, Preventive and Pediatric Dentistry, School of Dental Medicine, University of Bern, Bern, Switzerland; Adjunct Professor, Division of Restorative and Prosthetic Dentistry, The Ohio State University, Columbus, Ohio; and Adjunct Professor,Department of Prosthodontics, Faculty of Dentistry, Lokman Hekim University, Ankara, Turkey.
[g]Senior Research Associate, Department of Reconstructive Dentistry and Gerodontology, School of Dental Medicine, University of Bern, Bern, Switzerland.
[1]F.C.A. and M.B.D.contributed equally to this article and share first authorship

Clinical Implications

The tested bio-based dental cast resin may be a more reliable and potentially ecologically sustainable alternative to other tested resins for the additive manufacturing of removable dies and corresponding partial arch dental casts.

Making conventional impressions and obtaining stone casts have long been a part of the standard workflow to fabricate dental prostheses.[1,2] Advancements in computer-aided design and computer-aided manufacturing (CAD-CAM) technology enabled the use of intraoral scanners (IOSs) for digitizing intraoral conditions and fabricating prostheses in a direct digital workflow.[3,4] In addition, CAD-CAM technologies enable manufacturing of physical casts, which may involve removable dies, from the patients' digital scan data, particularly for complex situations and to improve the esthetics of the prostheses.[5,6] Although both additive (AM) and subtractive (SM) manufacturing can be used to create removable dies and dental casts,[7,8] AM is more commonly preferred in dental clinics and laboratories[9,10] as it reduces excess raw material[11] and is well-suited for producing complex designs such as removable dies because of their multi-geometry regions.[1,12,13]

Unlike conventional removable stone dies that are seated into casts with pins or their conical root portions,[14] AM removable dies are fabricated and post-processed separately from the definitive cast and then assembled for subsequent steps.[9] Since precise prosthesis fabrication relies on the accuracy of removable dies and their fit in definitive casts, understanding the factors influencing these aspects is essential.[9] The resin used for the fabrication is among the many factors that could impact the fabrication accuracy and dimensional stability of AM dental appliances.[3,15–19] However, most of the available dental cast resins comprise petroleum derivatives and have increased carbon footprint.[20,21] In this respect, bio-based resins with low toxicity and acceptable properties have become an ongoing subject of interest,[21–27] and such resins have been recently introduced for dental AM applications.[3,28,29] Integrating bio-based resins into daily practice of clinicians and dental laboratory technicians may improve the overall sustainability of AM processes.

Long-term dimensional stability is an essential factor for the success of AM dental cast resins,[3] as repeatedly fabricating the same casts and removable dies is not environmentally sustainable, regardless of the resin material used. A nanographene-reinforced dental cast resin has been recently developed to address this issue with the fabrication of dimensionally stable and defect-free casts.[16,30] Graphene, a carbon allotrope, acts as a reinforcing agent in polymers,[31–33] potentially enhancing the resistance of dies or casts made from this resin to dimensional changes over time.

Previous studies have tested the fabrication trueness and fit of AM removable dies,[1,5,7,12,13,17,34–38] but only one examined nanographene-reinforced resin,[1] and their dimensional stability remains largely unexplored.[13,37] While dentate casts made from bio-based and nanographene-reinforced resins have shown clinically acceptable stability,[3,16] their use as removable dies has not been investigated. Therefore, this study evaluated the dimensional stability and fit of AM removable dies over 4 weeks using different cast resins. The null hypotheses were that resin type, die region, and time point would not affect the dimensional stability, and resin type and time point would not affect the fit of AM removable dies.

MATERIAL AND METHODS

The mandibular right first molar of a typodont model (ANA-4; Frasaco GmbH) was prepared for a crown with a 1-mm-wide chamfer finish line and a partial arch scan with adjacent premolar and molar teeth was performed with an IOS (CEREC Primescan v5.2; Dentsply Sirona). The standard tessellation language (STL) file of this partial arch scan was imported into a CAD software program (DentalCAD 3.0 Galway; exocad GmbH) and the model creator tool was used to design a removable die-sectioned hollow cast.[1,5] After the designs had been completed, the reference STL files of the removable die (DR-STL) and hollow partial arch cast with (CRW-STL) and without (CR-STL) the die were exported for further processing.

To fabricate the removable dies and hollow casts (Fig. 1), DR-STL and CR-STL were imported into the nesting software program (Composer v2.0; Asiga) of a digital light processing-based 3D printer (MAX UV; Asiga). After nesting both STLs with their base parallel to the build platform and generating the supporting structures automatically, the DR-STL was duplicated until 16 dies were placed on the build platform. A dental cast resin (DentaMODEL; Asiga) (AM-DM), a bio-based dental cast resin (FotoDent biobased model; Dreve GmbH) (AM-FD), and a nanographene-reinforced dental cast resin (G-Print; Graphenano Dental) (AM-GP) were then used to fabricate a total of 48 removable dies and 3 hollow casts with a standardized layer thickness of 100 μm.[5] The AM-DM served as the control group, and detailed information on the experimental materials is provided in Table 1. The sample size was determined according to a power analysis (95%

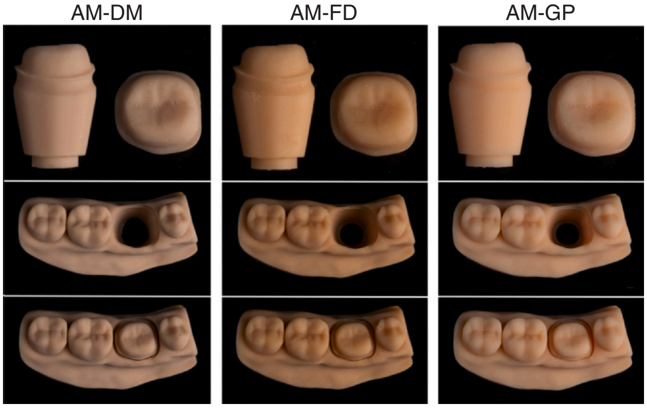

Figure 1. Representative images of removable dies and partial arch casts for each tested resin. AM-DM, DentaMODEL; AM-FD, Fotodent biobased model resin; AM-GP, G-Print.

confidence (1-α), 95% test power (1-β), and effect size f=1.489) based on the results of a previous study.[1]

After the fabrication, all removable dies and hollow casts were cleaned to remove excess resin and post-polymerized (Table 2). One day after the fabrication, the same IOS (CEREC Primescan v5.2; Dentsply Sirona) was used to generate the test STL files of the removable dies (DT-STLs) and the dies seated into their respective hollow casts (CTW-STLs) to minimize dimensional changes.[1,5] These scans were recorded as T0 scans and repeated weekly for 1 month (T1–T4). All scans were performed by 1 operator (F.C.A.), who calibrated the IOS before each scan cycle. The scans were performed under standardized temperature, humidity, and lighting conditions, with all dies and casts stored in lightproof boxes between scans to minimize environmental effects.

After the scans had been completed, all STLs were imported into a metrology-grade 3D analysis software program (Geomagic Control X v2022.1; 3D Systems). The first step of dimensional stability analyses was to import the DR-STL to virtually separate it into 3 regions (crown, root, and base of the root) with the region tool. Then, DT-STLs from each time point were superimposed over this segmented DR-STL with the initial and iterative closest point algorithm-based best fit alignments. The software program automatically computed RMS deviations and color maps (±10 µm tolerance, ±100 µm nominal) were generated using the 3D compare tool for qualitative analysis (Figs. 2–4). The same tool was also used to virtually separate the crown portion of the removable die and the adjacent teeth on the CRW-STL. Each CTW-STL was then superimposed over the segmented CRW-STL with the initial and best fit alignment algorithms after excluding the crown portion of the removable die with the "use selected data only" feature of the best-fit alignment tool. The RMS values of the adjacent teeth were collected for each CTW-STL and averaged to evaluate the potential effect of the 3D printer and IOS on measured deviations of partial arch casts with dies.

The fit of the removable dies were quantitatively and qualitatively analyzed with the RMS values and color maps of the crown portion of the dies when seated in the partial arch cast (Figs. 5–7) along with a previously used point-based measurement.[1,5] For the point-based measurements, a 2-dimensional plane that passed through the crown portion of the die in mesiodistal direction was generated and 5 points (most distal point of the margin, tip of the distal cusp, deepest point of the occlusal fossa, tip of the mesial cusp, and most mesial point of the margin) were virtually selected on the CRW-STL and CTW-STLs (Fig. 8). The distance deviations between these points were automatically calculated by the analysis software program as a negative or a positive value. A negative value indicated that the point on the CTW-STL was below its corresponding point on the CRW-STL and a positive value indicated otherwise. The absolute values of these distance deviations were used for statistical analysis.

The data distribution was assessed using the Kolmogorov-Smirnov test, while variance homogeneity was evaluated with the Levene test. The measured data followed a normal distribution (P>.05). Although the crown portion's deviations in the dentate cast (F=1.37, P=.057) did not violate the assumption of homogeneity, dimensional stability (F=2.48, P=.004) and point-based deviation (F=2.30, P=.046) data exhibited heteroscedasticity. Therefore, a generalized linear model analysis was performed, given its robustness to heteroscedasticity. All analyses were performed with a software program (Minitab Software V.17; Minitab, LLC) (α=.05).

Table 1. Dental cast resins tested

Material	Abbreviation	Chemical Composition	Viscosity (mPa·s)
DentaMODEL	AM-DM	7,7,9(or 7,9,9)- trimethyl–4,13-dioxo3,14-dioxa–5,12- diazahexadecane–1,16- diyl bismethacrylate, tetrahydrofurfuryl methacrylate, diphenyl(2,4,6- trimethylbenzoyl) phosphine oxide,	400
FotoDent biobased model	AM-FD	Acrylic oligomer: ≥ 50% Fatty acids, C18-unsatd., dimers, polymers with acrylic acid and 1,3,5-tris(2-hydroxyethyl)–1,3,5-triazine–2,4,6(1 H,3 H,5 H)- trione: ≥1–<10%	600
G-Print	AM-GP	Not disclosed	552

Table 2. Postprocessing parameters used

Resin	Cleaning	Postpolymerizaiton
AM-DM	5 min of prewash and 5 min of postwash with 98% isopropanol in an ultrasonic cleaner	2×2000 flashes under nitrogen gas atmosphere (Otoflash G171; NK Optical GmbH)
AM-FD	6 min of prewash and 6 min of postwash with 98% isopropanol in an ultrasonic cleaner	2×4000 flashes under nitrogen gas atmosphere (Otoflash G171; NK Optical GmbH)
AM-GP	5 min of washing with 98% isopropanol in an ultrasonic cleaner	2×2000 flashes under nitrogen gas atmosphere (Otoflash G171; NK Optical GmbH)

RESULTS

The interaction between resin type and region on the die, between resin type and time point, and each main factor affected the dimensional stability of removable dies ($P \leq .020$). AM-GP led to higher crown region RMS than AM-FD ($P<.001$). AM-DM led to the highest root and base of the root RMS ($P \leq .027$) and AM-FD resulted in the lowest overall RMS ($P \leq .038$). Regardless of the resin type, the base of the root region had the highest RMS, followed by the root and overall regions ($P<.001$). AM-FD led to lower RMS than AM-GP at T0 ($P<.001$) and AM-DM at T2 ($P=.003$). AM-GP led to lower RMS than AM-DM at T1 ($P=.010$). AM-GP dies had lower RMS at T1 than at T0 and T3 ($P<.001$). Among tested resins, AM-FD had the lowest RMS ($P<.001$), and T4 RMS were lower than T3 RMS ($P=.008$) (Table 3).

The resin, time point, and the interaction between these factors affected the RMS values of the crown portion of the die when seated in the cast ($P<.001$). Regardless of the time point, AM-FD led to the lowest and AM-DM led to the highest RMS ($P<.001$). AM-DM dies had their lowest RMS at T0 ($P<.001$), while those measured at T4 were higher than at T1 ($P=.003$). T0 RMS were the lowest ($P<.001$), and T1 RMS were lower than T4 RMS ($P=.011$) (Table 4). Table 5 shows the RMS values of the partial arch dentate cast within each resin-time point pair.

When the point-based deviations were considered, resin, time point, and the interaction between these factors affected measured values ($P<.001$). Regardless of the time point, AM-FD led to the lowest and AM-DM led to the highest deviations ($P<.001$). AM-DM dies had their lowest deviations at T0 ($P<.001$) and AM-FD dies had their highest deviations at T4 ($P \leq .034$). The deviations measured at T0 were the lowest ($P \leq .009$), while those measured at T4 were higher than the remaining time points ($P \leq .041$), except for T3 ($P=.171$) (Table 6). The distribution of raw point-based data is given in Figure 9.

DISCUSSION

Overall and region-based RMS values for removable dies were different among tested AM dental cast resins

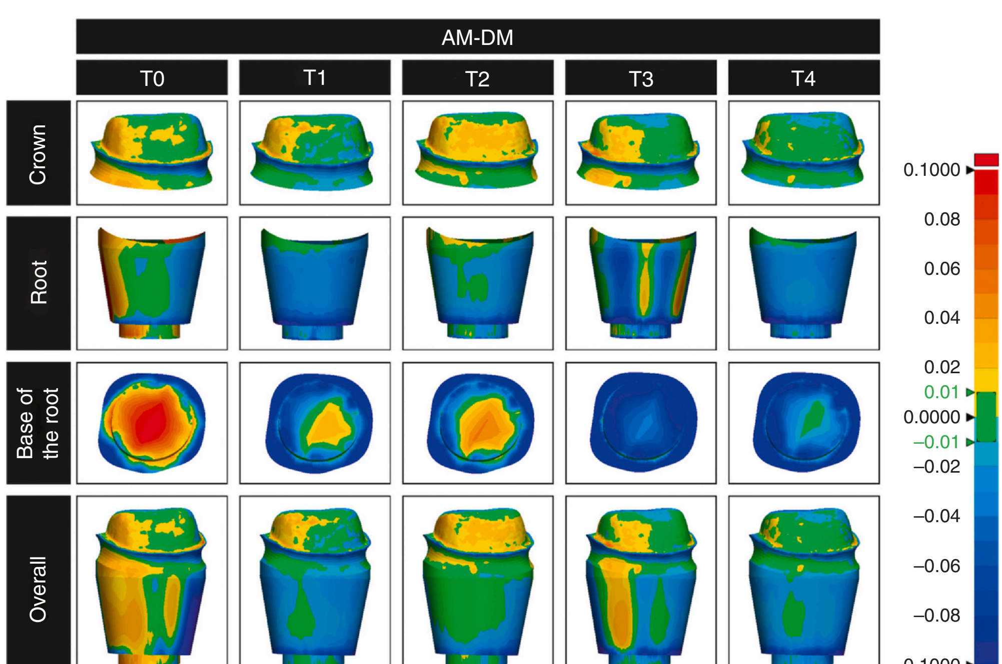

Figure 2. Representative color maps of different portions of AM-DM removable die. AM-DM, DentaMODEL; T0, One day after fabrication; T1, One week after fabrication; T2, Two weeks after fabrication; T3, Three weeks after fabrication; T4, Four weeks after fabrication.

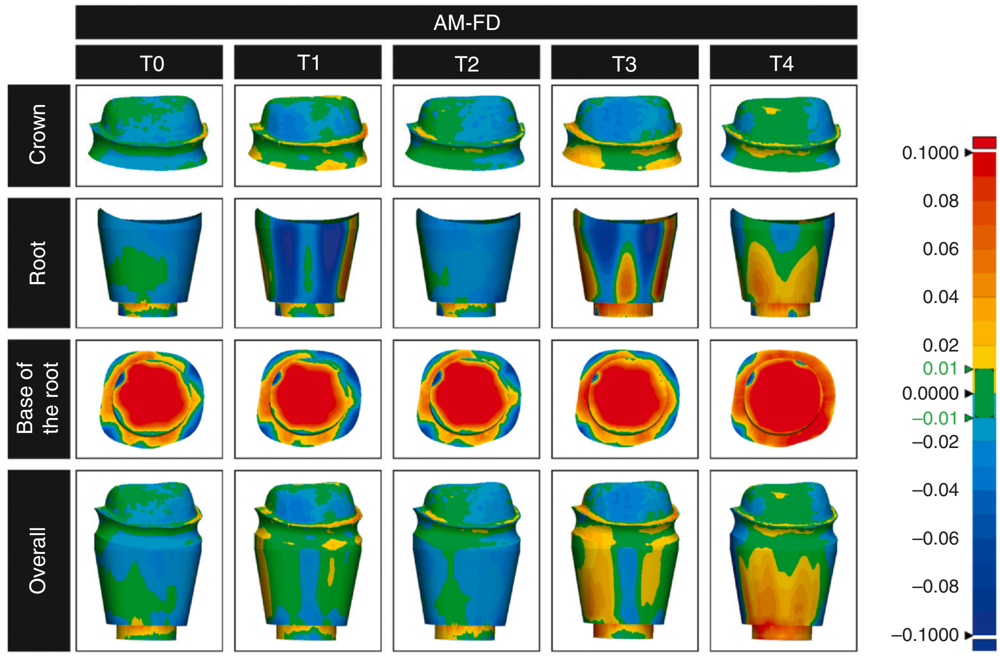

Figure 3. Representative color maps of different portions of AM-FD removable die. AM-FD, Fotodent biobased model resin; T0, One day after fabrication; T1, One week after fabrication; T2, Two weeks after fabrication; T3, Three weeks after fabrication; T4, Four weeks after fabrication.

and time points. Moreover, the fit of the dies and the RMS values of the portion of the crown of seated dies were significantly impacted by resin type and time point. Therefore, the null hypotheses that resin type, die region, and time point would not affect the dimensional stability, and resin type and time point would not affect the fit of AM removable dies were rejected.

Significant differences were observed among the tested AM removable dies within tested regions, but the greatest mean RMS difference was 17.4 µm (base of the root, AM-DM and AM-GP), which may be clinically negligible. The base of the root region showed the highest RMS within each resin, with the greatest difference being 62.3 µm (with crown region within AM-

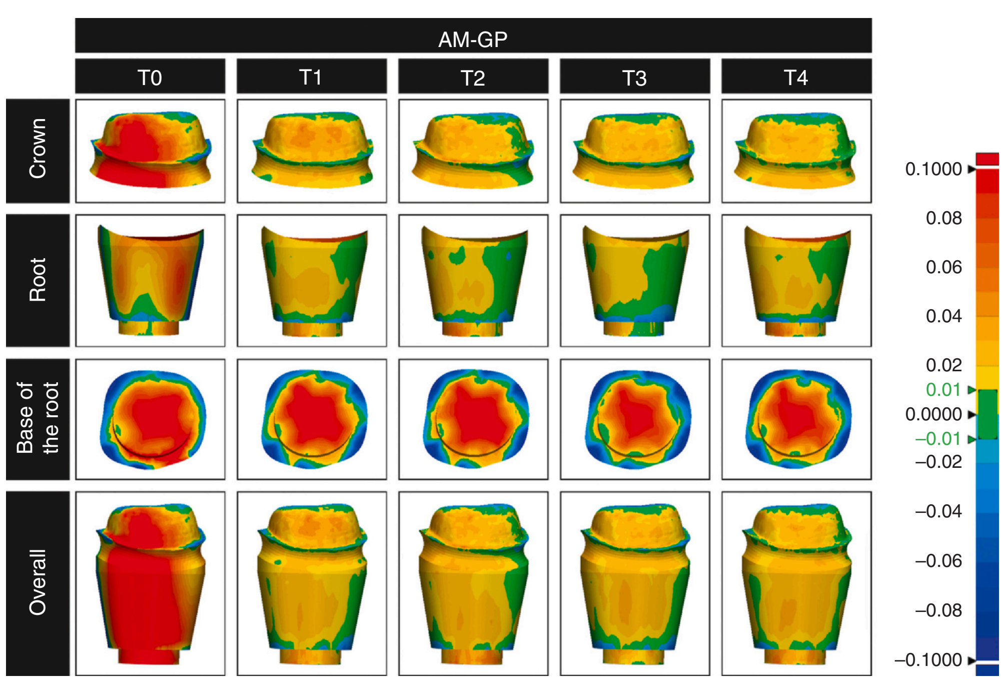

Figure 4. Representative color maps of different portions of AM-GP removable die. AM-GP, G-Print; T0, One day after fabrication; T1, One week after fabrication; T2, Two weeks after fabrication; T3, Three weeks after fabrication; T4, Four weeks after fabrication.

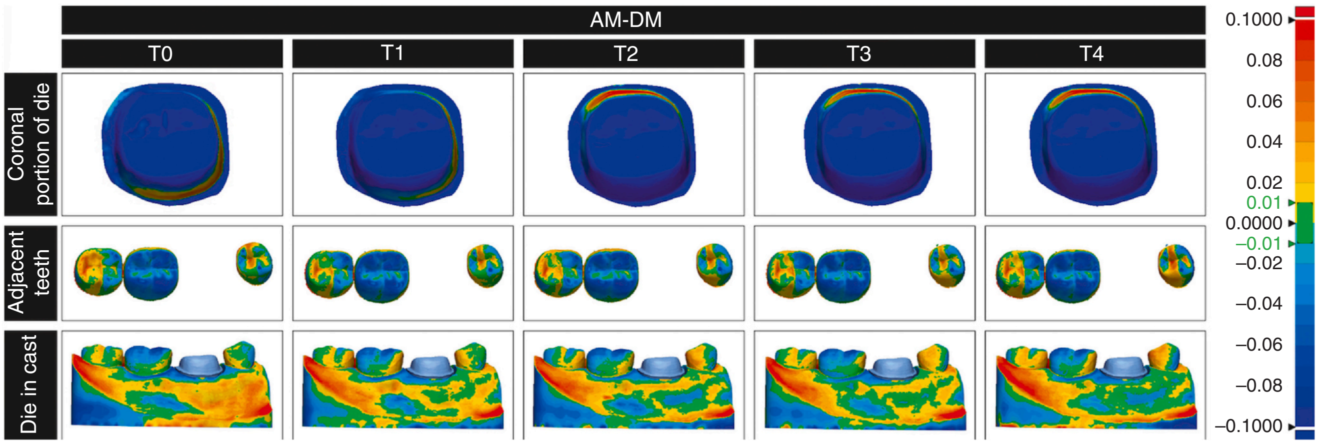

Figure 5. Representative color maps of AM-DM removable die seated on cast. AM-DM, DentaMODEL; T0, One day after fabrication; T1, One week after fabrication; T2, Two weeks after fabrication; T3, Three weeks after fabrication; T4, Four weeks after fabrication.

DM), but this region had manual adjustments, making such a difference clinically challenging to detect. When considering time points, these differences were even smaller and potentially imperceptible, with the greatest mean RMS difference among tested removable dies being just 9.8 µm (AM-FD and AM-GP at T3) and among tested time points being just 10 µm (T0 or T3 and T1, AM-GP). Therefore, qualitative analysis of the color maps is essential to understanding the clinical impact of the measured deviations over 4 weeks. In this study, the AM-FD dies generally had lower RMS, while the AM-DM dies showed the highest RMS in the root and base regions. The color maps of AM-DM dies displayed a varied color distribution: yellow dominated at T0, indicating slight overcontouring, while at T1, green and light blue were more prominent, suggesting increased polymerization shrinkage. At T2 and T3, yellow zones reappeared, likely because of the linear expansion, with green becoming dominant at T4. Significant deviations were observed in the base region at T0, with red zones linked to manual support removal, while green appeared at T1 and T2, and dark blue at T3 and T4, indicating undercontouring. These findings align with a previous study on the dimensional stability of AM-DM casts,[16] where light blue, yellow, and green were dominant on the labial and palatal surfaces, while red was dominant on the incisal edges. Therefore, it can be assumed that dental appliances in AM-DM resin exhibit greater dimensional stability along the x-y axis than along the z axis. Bio-based AM resins have been previously investigated in terms of dentate and implant casts[3,28]; however, they have not been explored as options for removable dies. In the present study, the AM-FD dies mostly had higher dimensional stability than the AM-DM and AM-GP dies. Color maps of the AM-FD dies showed green and light blue in the crown region, indicating minor deviations and good dimensional stability. In contrast, the root regions showed increased yellowness over time, suggesting slight distortion that could affect positioning if stored more than a month. The red zones at the base of the root may be related to the difficulties in removing supporting structures

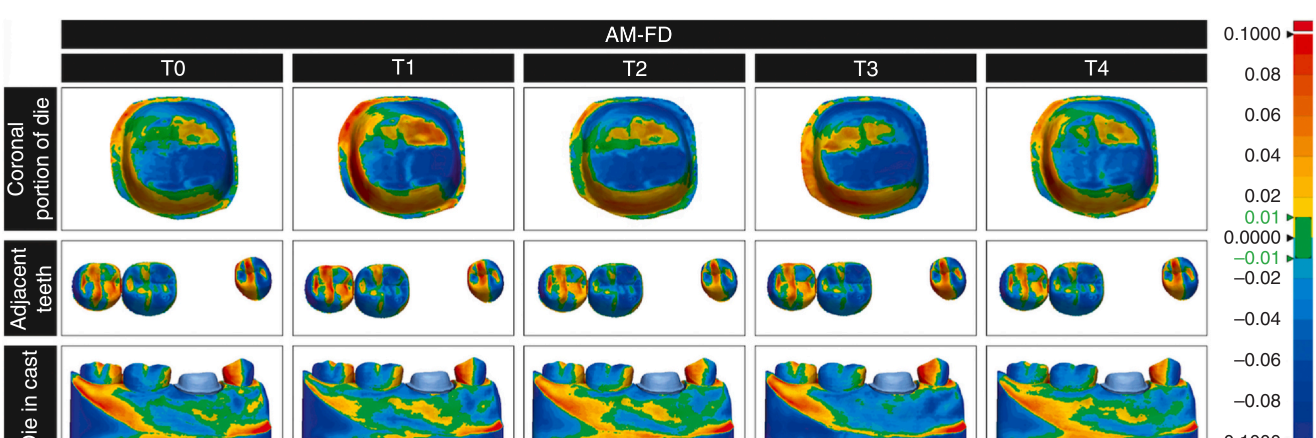

Figure 6. Representative color maps of AM-FD removable die seated on cast. AM-FD, Fotodent biobased model resin; T0, One day after fabrication; T1, One week after fabrication; T2, Two weeks after fabrication; T3, Three weeks after fabrication; T4, Four weeks after fabrication.

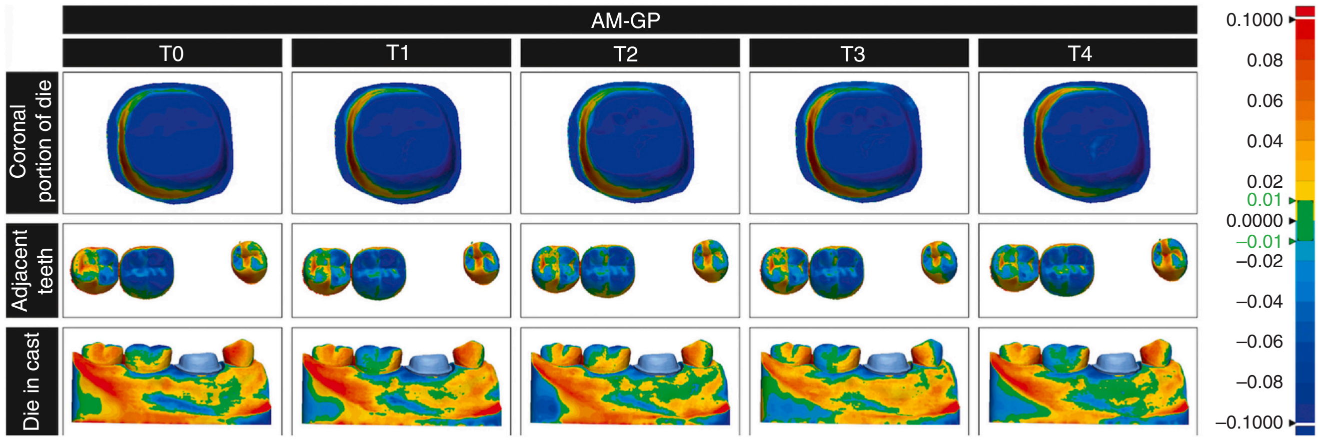

Figure 7. Representative color maps of AM-GP removable die seated on cast. AM-GP, G-Print; T0, One day after fabrication; T1, One week after fabrication; T2, Two weeks after fabrication; T3, Three weeks after fabrication; T4, Four weeks after fabrication.

because of the resin's higher viscosity. These findings align with a previous study on the dimensional stability of the same bio-based AM resin,[3] which attributed its stability to a prolonged polymerization period compared with the other tested resins, thereby limiting the ongoing distortion of AM-FD. AM-GR dies' color maps at T0 showed dominating red demarcations, signifying overcontours. This was supported by a previous study on the dimensional stability of AM-GR casts,[16] which attributed the observed distortion to the presence of graphene, potentially interfering with the adhesion of subsequent printable resin layers. The significantly higher crown RMS values suggest that occlusal and interproximal adjustments may be necessary for AM-GP

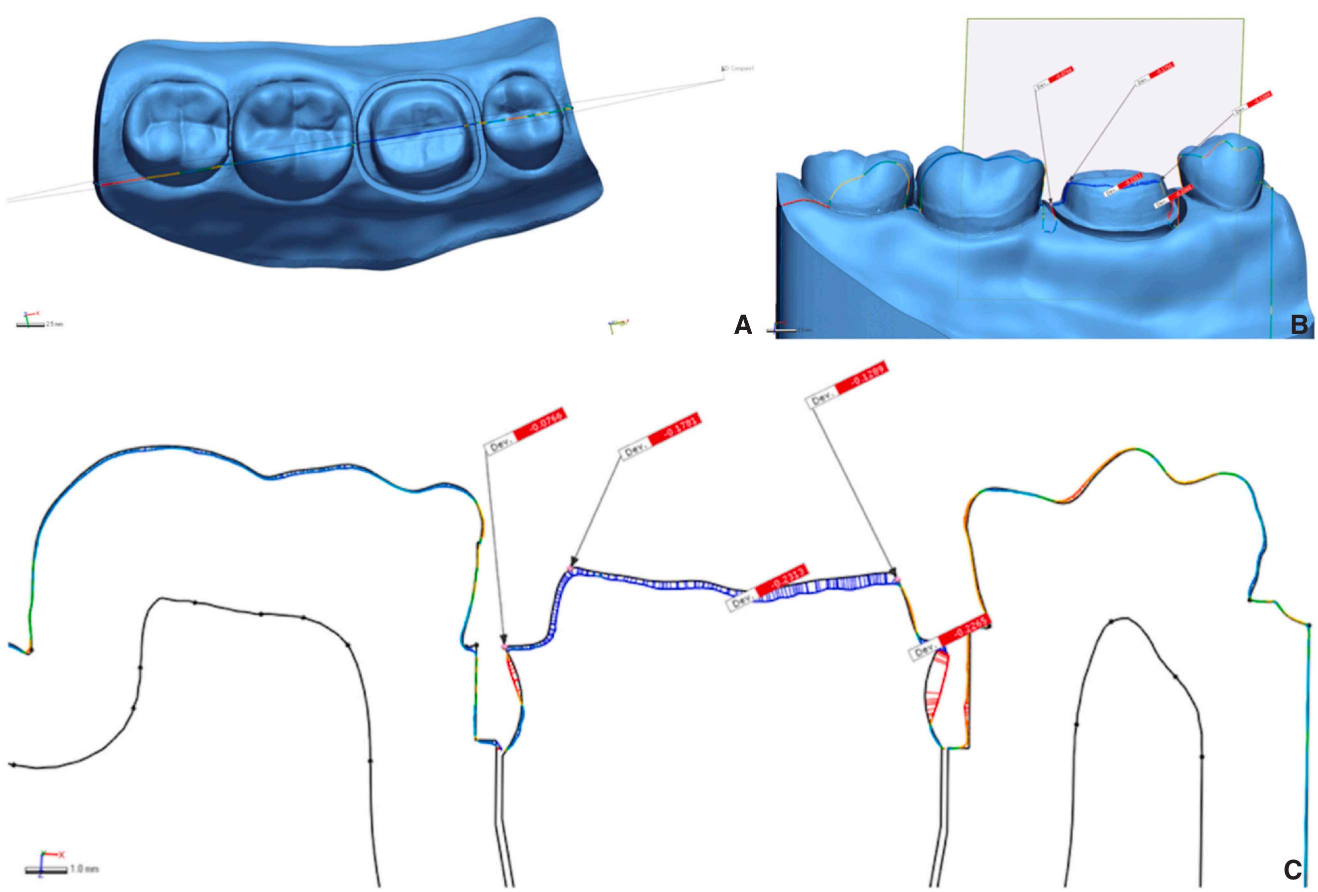

Figure 8. Fit analysis of removable dies based on point-based measurement. A, Mesiodistally oriented virtual plane. B, Points generated on removable die. C, Cross-sectional view of generated points.

Table 3. Mean ±standard deviation overall and region-based RMS values (µm) of AM removable dies

	Resin			
Region	**AM-DM**	**AM-FD**	**AM-GP**	**Pooled region data**
Crown	26.4 ±7.3^{AB}	21.7 ±7.5^{A}	33.5 ±16.7^{BC}	27.2 ±12.4*
Root	61.4 ±13.3^{F}	52.7 ±10^{E}	53.5 ±21.7^{E}	55.9 ±16.2$^{\#}$
Base of the root	88.7 ±20.2^{H}	78.5 ±13.7^{G}	71.3 ±10.8^{G}	79.5 ±16.9
Overall	43.2 ±9.9^{D}	35.4 ±8.6^{C}	43.1 ±19.5^{D}	40.6 ±14.0$^{\wedge}$
Time point				**Pooled time point data**
T0	47.1 ±24.7^{abc}	41.3 ±23.0^{a}	51.2 ±22.2^{c}	46.5 ±23.5$^{*\wedge}$
T1	49.2 ±26.9^{bc}	43.6 ±24.5^{ab}	41.2 ±16.2^{a}	44.7 ±23.1$^{*\wedge}$
T2	50.8 ±27.6^{c}	42.1 ±24.3^{a}	46.5 ±19.7^{abc}	46.5 ±24.2$^{*\wedge}$
T3	50.8 ±30.3^{c}	41.4 ±24.2^{a}	51.2 ±28.9^{c}	47.8 ±28.2$^{\wedge}$
T4	46.4 ±25.4^{abc}	40.8 ±22.7^{a}	44.2 ±19.7^{abc}	43.8 ±22.7*
Pooled resin data	48.9 ±27.0$^{\wedge}$	41.9 ±23.6*	46.9 ±22.0$^{\wedge}$	

Different superscript uppercase letters indicate significant differences among resin-region pairs, while different superscript lowercase letters indicate significant differences among resin-time point pairs. Different superscript symbols indicate significant differences among resins, regions, and time points (P<.05).

Table 4. Mean ±standard deviation root mean square values (µm) of crown portion of dies when seated in partial arch casts within each resin-time point pair

	AM-DM	**AM-FD**	**AM-GP**	**Pooled time point data**
T0	144.5 ±15.1^{c}	54.5 ±12.3^{a}	94.7 ±13.9^{b}	97.9 ±39.6^{A}
T1	187.9 ±26.7^{d}	55.5 ±12.4^{a}	90.8 ±12.8^{b}	111.4 ±59.4^{B}
T2	198.6 ±11.7^{ed}	49.7 ±9.5^{a}	93.4 ±9.1^{b}	113.9 ±63.9^{BC}
T3	200.6 ±13.5^{ed}	53.8 ±8.7^{a}	94.6 ±9.9^{b}	116.3 ±63.4^{BC}
T4	207.4 ±11.9^{e}	61.6 ±7.3^{a}	91.6 ±8.3^{b}	120.2 ±64.2^{C}
Pooled resin data	187.8 ±27.9^{C}	55.0 ±10.7^{A}	93.0 ±10.8^{B}	

Different superscript lowercase letters indicate significant differences among resin-time point pairs, while different superscript uppercase letters indicate significant differences among resins or time points (P<.05)

dies at T0. However, over time, the color maps transitioned to predominantly yellow with speckled green zones, which could indicate delayed polymerization shrinkage.

The fit of the removable dies was assessed using RMS values for the crown portion when seated in their respective dentate partial arch casts, along with point-based analysis. The AM-DM dies showed the highest RMS values at all time points. Also, both AM-DM and AM-GP seated dies had higher RMS values than their corresponding dentate casts without dies. This suggests an incompatible dimensional behavior of the AM-DM and AM-GP seated dies relative to their encompassing casts, leading to accumulated errors, with the greatest dimensional disparity observed in the AM-DM die and cast complex. In contrast, the AM-FD seated dies showed RMS values within the range of their respective dentate casts, indicating synchronized dimensional stability. The threshold for acceptable RMS in AM casts used for prosthetic applications is 200 µm,[15] and all partial arch casts exhibited acceptable deviations within the one-month period. Although the crown portion RMS of the AM-DM dies, when seated in their partial arch cast, exceeded this limit at T3 and T4, the greatest difference was only 7.4 µm, which is potentially clinically negligible. Additionally, the measured crown portion RMS values may have been affected by the RMS values of the partial arch casts, and the potential effect of the

Table 5. Overall mean deviation values (µm) of dentate partial arch casts without die within each resin-time point pair

	AM-DM	**AM-FD**	**AM-GP**
T0	35.4	57.9	50.5
T1	35.1	56.3	48.7
T2	36.4	54.2	46.8
T3	38.4	54.8	49.8
T4	38.6	56.3	49.3

dies' position in their casts on the occlusal and interproximal contacts of the definitive prostheses may be smaller.[5] Nevertheless, restoration adjustments on AM-DM dies should be made promptly because of the significant changes in the crown portion RMS over time. Even though both the seated AD-FD and AM-GP dies displayed RMS values within the acceptable range,[15] the AD-FD dies had significantly lower RMS values, suggesting they may be more suitable for long-term use compared to AM-GP dies. Color maps of the crown portion of seated dies supported these findings, with AM-DM and AM-GP dies mainly showing dark blue, indicating circumferential undercontouring, while AM-FD dies displayed mixed patterns, reflecting both undercontouring and overcontouring. Point-based fit analysis revealed greater deviations of AM-DM dies compared to the other dies, indicating a more significant decline in the dimensional stability of seated AM-DM dies compared to free-standing dies and the casts. This

Table 6. Mean ±standard deviation values of point-based deviations (μm) within each resin-time point pair

	AM-DM	AM-FD	AM-GP	Pooled time point data
T0	194.1 ±17.4^{d}	44.5 ±15.8^{a}	136.9 ±32.5^{c}	125.2 ±66.3^{A}
T1	239.6 ±30.1^{e}	48.3 ±14.6^{a}	131.8 ±29.8^{c}	139.9 ±83.1^{B}
T2	254.1 ±19.2^{e}	40.9 ±8.3^{a}	138.4 ±24.4^{c}	144.5 ±89.9^{B}
T3	253.8 ±19.7^{e}	48.2 ±11.4^{a}	139.2 ±29.7^{c}	147.1 ±87.6^{BC}
T4	258.2 ±16.5^{e}	75.6 ±10.9^{b}	137.2 ±25.4^{c}	157.0 ±78.8^{C}
Pooled resin data	240.0 ±31.6^{C}	51.5 ±17.4^{A}	136.7 ±27.9^{B}	

Different superscript lowercase letters indicate significant differences among resin-time point pairs, while different superscript uppercase letters indicate significant differences among resins or time points. Total values are derived from pooled data (*P*<.05)

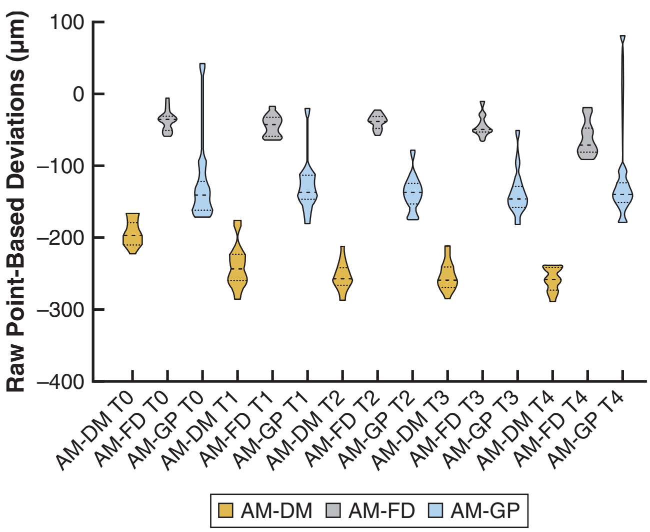

Figure 9. Distribution of raw point-based distance measurement data. AM-DM, DentaMODEL; AM-FD, Fotodent biobased model resin; AM-GP, G-Print; T0, One day after fabrication; T1, One week after fabrication; T2, Two weeks after fabrication; T3, Three weeks after fabrication; T4, Four weeks after fabrication.

could lead to accumulated errors in restoration dimensions, cement space, or occlusal and proximal contacts, requiring additional intraoral adjustments. Negative values in the raw point-based data across all tested groups suggest varying degrees of apical positioning, likely because of the subjective manual removal of supporting structures, which might have compromised the correct seating of the dies. Accordingly, it can be assumed that the definitive restorations adjusted on the tested dies may be veneered for adequate occlusal and interproximal contacts, which could lead to further intraoral adjustments.[1,34] Therefore, validating the positional trueness of AM removable dies is essential to prevent vertical discrepancies when seated on AM casts, using verification matrices.[9]

This study aimed to investigate the effect of dental cast resin type on the dimensional stability and fit of AM removable dies, comparing 2 recently introduced resins with a conventional one in a direct digital workflow. However, the absence of conventional dental stone dies was a limitation. In addition, the number of tested resins was limited to only 3 and one DLP-based 3D printer was used for all fabrication processes. The geometry of tested removable dies was another limitation, as different taper angles[1] and root geometries[17,34] may affect tested outcomes. In addition, the parameters used during the design stage of a die and a cast may affect the removable die's fit in that cast. The standardized layer thickness and build orientation of the dies and hollow casts were also a limitation. The absence of different storage media[10,11] was also a limitation. All test scans were performed with an IOS previously used in studies with similar outcomes[5,17] and reported to have accuracy comparable to extraoral scanners.[39] Using an IOS enabled continuous scanning of removable dies, avoiding errors from stitching multiple scans with an extraoral scanner. However, IOS data acquisition methods may impact results. Future studies should assess crown contact adjustment efficiency on tested dies to enhance their clinical applicability, particularly for those in AM-FD and AM-GP resins.

CONCLUSIONS

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

1. Within tested die regions and time points, additively manufactured removable dies in bio-based dental cast resin mostly had higher dimensional stability. The crown region of the dies had the highest and the base of the root region of the dies had the lowest dimensional stability. The effect of time on dimensional stability was small.
2. Regardless of the measurement method or time point, additively manufactured removable dies in bio-based dental cast resin exhibited the best fit, while those in conventional dental cast resin showed the worst fit.

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Corresponding author:
Dr Mustafa Borga Dönmez
Department of Reconstructive Dentistry and Gerodontology
School of Dental Medicine
University of Bern
Freiburgstrasse 7
Bern 3010
SWITZERLAND
Email: mustafa-borga.doenmez@unibe.ch

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CRediT authorship contribution statement

Fiona Cornelia Arnold: Investigation, Methodology. **Mustafa Borga Donmez**: Writing - original draft, Writing - review and editing. **Hanan Al-Johani**: Writing - original draft. **Çiğdem Kahveci**: Formal analysis. **Martin Schimmel**: Supervision, Writing - review and editing. **Burak Yilmaz**: Conceptualization, Supervision, Writing - review and editing. **Gülce Çakmak**: Conceptualization, Investigation, Methodology, Supervision.

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