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RESEARCH AND EDUCATION

Comparison of trueness and margin quality of additively and subtractively manufactured definitive resin-based laminate veneers

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ABSTRACT

Statement of problem. Currently available 3-dimensional (3D) additively manufactured (AM) resins used for definitive restorations have different chemical compositions and viscosities. The fabrication trueness and margin quality of laminate veneers additively manufactured with different resins have not been extensively studied.

Purpose. The purpose of this in vitro study was to evaluate the fabrication trueness and margin quality of AM and subtractively manufactured (SM) definitive resin-based laminate veneers.

Material and methods. A laminate veneer restoration for a maxillary right central incisor with a 25-μm cement space was designed to generate a reference laminate veneer standard tessellation language (STL) file (RLV-STL). This RLV-STL was used to fabricate resin-based laminate veneers (N=60) for definitive use, either using AM (a low-viscosity, urethane acrylate-based resin (CB Permanent, AM-LV), a high-viscosity, urethane acrylate-based resin (Tera Harz TC-80DP, AM-HV), and a glass-reinforced composite resin (Crowntec, AM-S) or SM (glass-filler reinforced composite resin blocks (Tetric CAD, SM) technologies. All laminate veneers were digitized with an intraoral scanner (CEREC Primescan SW 5.2) to generate their test STL files (TLV-STLs). RLV-STL and TLV-STLs were transferred into a 3D analysis software program (Geomagic Control X), and a trueness (external, intaglio, and marginal surface) analysis was performed by using the root mean square (RMS) method. The margin quality of laminate veneers was examined visually under a stereomicroscope and graded. The Kruskal-Wallis and Dunn tests were performed to analyze the data (α=.05).

Results. External, intaglio, and marginal RMS values showed statistically significant differences among test groups (*P*<.001). The SM group had the highest RMS values for the external surface (*P*<.001), whereas the AM-LV group had the lowest RMS values. The AM-HV group had the highest RMS values for the intaglio surface (*P*<.001). No significant difference was found between the SM and AM-HV groups for marginal RMS values, which were higher than for the other groups (*P*=.830). All average values for the axial mesial, axial distal, and incisal edge margin quality of laminate veneers were found to be similar and Grade 3 (smooth edge) in all groups.

Conclusions. Regardless of the evaluated surface, the fabrication technique affected the trueness of laminate veneers. The low-viscosity AM laminate veneers and AM laminate veneers reinforced with glass fillers had higher trueness than the SM laminate veneers at all surfaces. The low-viscosity AM laminate veneers had the highest trueness on external and marginal surfaces among the test groups and had higher trueness than the high-viscosity AM laminate veneers. (J Prosthet Dent 2025;133:184-192)

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Clinical Implications

Laminate veneers additively manufactured with low-viscosity urethane acrylate-based resin and glass-filler reinforced composite resin may require fewer chairside adjustments than when high-viscosity resin is used. However, high cervical margin quality can be achieved with tested, subtractively manufactured laminate veneers.

Since the early 1980s, laminate veneers have been commonly used for minimally invasive dentistry because of their high clinical success rates, esthetics, and function.[1,2] With the advancements in computer-aided design and computer-aided manufacturing (CAD-CAM) technologies, laminate veneers can be fabricated either by using subtractive manufacturing (SM) or additive manufacturing (AM) technologies in addition to leucite- and lithium disilicate-reinforced ceramic pressing and direct or indirect composite resin applications.[3,4] Because of the cost effectiveness and reduced material waste of AM, the 3-dimensional (3D) AM of definitive laminate veneers may provide advantages over SM.[5–7] An advantage of AM can be the reduction of vibration-induced fracture, chipping, or cracking of the restoration margins, which may occur during the milling of brittle materials.[8] In addition, because no layering is required, surface quality changes that may be seen with direct and indirect (layering technique) composite resin veneers and errors during laboratory steps of the pressing technique may be avoided.[9,10]

Recently, manufacturers have introduced several resins indicated for the AM of inlays and onlays,[11,12] crowns,[11–14] and laminate veneers.[11,12] Previous studies have evaluated the biocompatibility, mechanical properties (biaxial flexure strength), microhardness, and surface properties of those resins.[15–17] In addition, the production time, cost, fatigue behavior, retention, trueness, marginal gap, and fracture resistance of 3D-AM resin crowns have been evaluated for definitive use.[18–24] However, the authors are unaware of studies on the use of these resins for definitive laminate veneers.

The fabrication trueness of 3D-AM laminate veneers made of resins for definitive use, an essential factor for clinical success, determines the intaglio surface adaptation of the restoration.[25,26] Restorations with higher trueness require minimal internal and external adjustments, have little oral fluid and bacteria leakage and related microcracks and secondary caries, and maintain mechanical strength.[26–29] Earlier studies have reported that the laminate veneer material fabrication technique may affect marginal discrepancies and internal fit.[27,30] The chemical composition of a resin is important and may affect the 3D-AM process, fabrication trueness, and mechanical properties.[31] The rheological characteristics of a material can also challenge 3D-AM, as the material cannot be effectively refilled for subsequent layer formation. Resins with high viscosity have been reported to be challenging for 3D-AM because of their low flowability.[31,32] Currently available 3D-AM resins for definitive restorations vary in chemical composition and viscosity. The evaluation of the fabrication trueness and margin quality of veneers in various 3D-AM resins may broaden our knowledge of their clinical applicability. Therefore, the aim of the present study was to evaluate the fabrication trueness and margin quality of resin-based laminate veneers fabricated by using digital light processing (DLP) technology and 3 types of resins. Two different urethane acrylate-based resins for definitive use with different viscosities (low and high) and a glass-filler reinforced composite resin were compared with SM veneers in glass-reinforced composite resin. The null hypotheses were that the resin type would not affect the fabrication trueness measured on the external, intaglio, and margin surfaces of resin-based laminate veneers for definitive use and fabricated with AM or SM. The margin quality of laminate veneers from each group was also qualitatively evaluated.

MATERIAL AND METHODS

A maxillary right central incisor typodont tooth on a dentate model (ANA-4; frasaco GmbH) was prepared for a laminate veneer restoration. First, a silicone index was made from a heavy-body silicone impression material (Panasil Putty; Kettenbach GmbH & Co) to control the preparation depth. Then, a laminate veneer preparation was made by first preparing deep orientation grooves, which was followed by reduction with tapered round-ended diamond rotary instruments (801–010; Diatech). A butt-joint incisal overlap design with 1.5-mm incisal reduction without palatal chamfer along with an equigingivally located and interproximally extended 1-mm-wide chamfer finishing line and 1-mm labial reduction was prepared.[33–35] The preparation was finished with finishing stones (1096709; Diatech). The model was then digitized by using an intraoral scanner (CEREC Primescan SW 5.2; Dentsply Sirona), and a standard tessellation language (STL) file was generated. This STL file was imported into a dental design software program (exocad Dental CAD2.2; exocad GmbH), and a laminate veneer with a 25-µm cement gap with 40-µm minimal thickness was designed to generate a reference-laminate veneer STL file (RLV-STL) (Fig. 1).

A total of 45 resin-based laminate veneers for definitive use were manufactured by AM with a low-viscosity, urethane acrylate-based resin (C&B Permanent; ODS Co Ltd) (AM-LV), a high-viscosity, urethane acrylate-based resin (Tera Harz TC-80DP; Graphy) (AM-HV), or a glass-filler

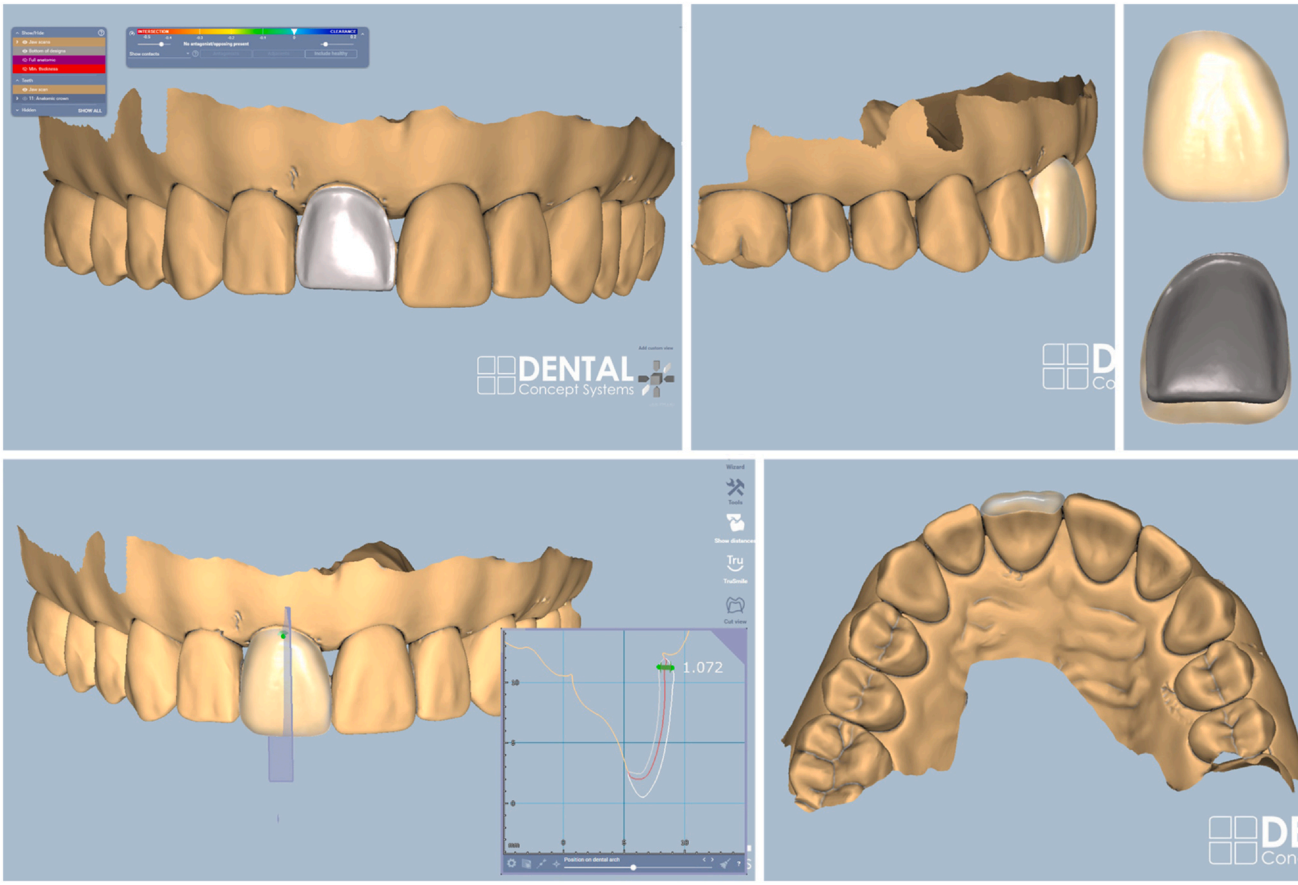

Figure 1. Laminate veneer design.

Table 1. Materials used

Material	Type	Composition	Manufacturer
Tetric CAD (SM)	Glass-filler reinforced composite resin for milling	Barium glass filler (% 64.0 by weight), silicon dioxide (% 7.1 by weight), dimethacrylates (% 28.4 by weight), additives & pigments (% 0.5 by weight)	Ivoclar AG
C&B Permanent (AM-LV)	Urethane acrylate-based resin for 3D-AM	Diurethane dimethacrylate, 2-Propenoic acid, 2-methyl-, (1-methylethylidene) bis (4,1-phenyleneoxy(1-methyl-2,1-ethanediyl)) ester, 2-HEMA, diphenyl (2,4,6- trimethylbenzoyl) phosphine oxide, and additives	ODS Co, Ltd
Crowntec (AM-S)	Glass-filler reinforced composite resin for 3D-AM	Up to 50% in weight, 0.7-mm barium aluminum borosilicate glass fillers, 4,4′-isopropylidiphenol, ethoxylated and 2-methylprop-2enoic acid, silanized dental glass, pyrogenic silica, catalysts, inhibitors.	Saremco Dental AG
Tera Harz TC-80DP (AM-HV)	Urethane acrylate-based resin for 3D-AM	Urethane acrylate oligomer, bisphenol A ethoxylate dimethacrylate, 2-HEMA, diphenyl (2,4,6- trimethylbenzoyl) phosphine oxide, and additives	Graphy

HEMA, hydroxyethyl methacrylate; HV, high-viscosity; LV, low-viscosity; 3D-AM, 3-dimensionally additively manufactured.

reinforced composite resin (Crowntec; Saremco Dental AG) (AM-S). The viscosities of the AM-LV and AM-HV groups were 150 ±100 cP and 2000 ±300 cP, respectively, according to the manufacturer information. The viscosities of the 3D-AM resins were measured using a capillary glass viscometer (Fisherbrand Glass Opaque Calibrated Viscometer Tubes; Fischer Scientific). The viscosities were 151 cP for AM-LV, 3525 cP for AM-HV, and 2600 cP for AM-S. In addition, 15 CAD-CAM laminate veneers were fabricated by SM with glass-filler reinforced composite resin blocks (Tetric CAD; Ivoclar AG) (SM) (Table 1). The sample size for this study (n=15) was determined based on priori power analysis (for 95% CI (1-α), 95% power (1-β), and an effect size of f=0.623).[36]

To fabricate laminate veneers for AM-LV, AM-HV, and AM-S groups, the RLV-STL was imported into a build preparation software program (Composer; Asiga) for nesting and slicing. Corresponding resins with a 50-µm layer thickness were selected, and the RLV-STL was positioned with the incisal edge facing toward the build platform. Support structures were generated automatically without supports on the intaglio surface. These

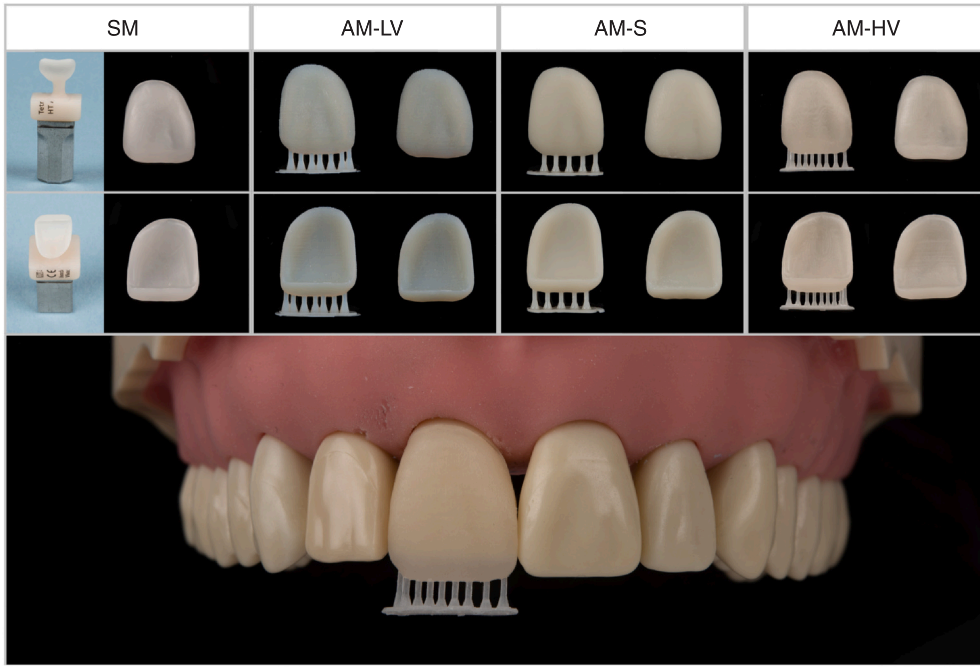

Figure 2. Additively (AM) and subtractively (SM) manufactured laminate veneers. AM-HV, Tera Harz TC-80DP; AM-LV, C&B Permanent; AM-S, Crowntec; SM, Tetric CAD. HV, high-viscosity; LV, low viscosity.

configurations were duplicated 15 times per resin for standardization. Laminate veneers were printed by using a DLP-based 3D printer (MAX UV; Asiga). After a 10-minute drip time, laminate veneers were removed from the build platform, and the support structures were then cut off with a side cutter. For the postprocessing, AM-HV and AM-LV specimens were cleaned in an ultrasonic bath of 96% ethanol (Ethanol Absolut; Dr. Grogg Chemie AG) for 45 seconds and further cleaned with an ethanol-soaked cloth until all unpolymerized resin was removed. AM-S specimens were cleaned with a 96% ethanol-soaked cloth until all resin remains were removed without ultrasonic cleaning as recommended by the manufacturer. The specimens were then dried by using an air syringe and allowed to dry for at least 10 minutes to ensure that they were free of alcohol residue and polymerized with 4000 (2 × 2000, 5 minutes cool-down between the 2 sets of exposures) lighting exposures using a xenon lamp-polymerization unit (Otoflash G171; NK Optik GmbH).[21] To fabricate laminate veneers for the SM group, RLV-STL was imported into a nesting software program (PrograMill CAM V4.2; Ivoclar AG) and wet milled with a 5-axis milling unit (PrograMill PM7; Ivoclar AG) (n=15) from a composite resin CAD-CAM block (Tetric CAD HT; Ivoclar AG). The milling settings were selected in accordance with the manufacturer's instructions.

All veneers were then steam-jet cleaned air-dried, and evaluated for defects (Fig. 2). The support remnants were removed under magnification loupes (EyeMag Pro ×3.5; Carl Zeiss), and the surfaces were smoothed to prevent errors during the alignment procedure. Except for the incisal edges, no adjustments were made to the intaglio surface. One experienced operator (G.C.) performed all AM and SM fabrication processes.

The laminate veneers were kept in dry and lightproof boxes to be scanned within 2 days of fabrication. An operator (D.Y.) with more than 2 years of experience in digital scanning scanned the entire anatomy of the laminate veneers to generate test-STLs by using the same intraoral scanner. All scans were performed in the same temperature- and humidity-controlled room under ambient light. The intraoral scanner was calibrated before each 5 specimens and the operator took 5-minute breaks in between to minimize fatigue-related deviations. The scans were evaluated for errors and converted to the test STL files (TLV-STLs).

To analyze the fabrication trueness of veneers, a 3D inspection software program (Geomagic Control X; 3D Systems) was used. The reference STL file (RLV-STL) was imported, moved to the reference data, and digitally segmented into 3 regions to further analyze deviations at the external, intaglio, and margin surfaces (Fig. 3) by using the "Region Tool" of the software program. This file was saved as a reference template to further inspect the 3D deviations of all laminate veneers by superimposing them on this file. Then, the test STL file (TLV-STL) of each laminate veneer was imported, and an initial alignment was done, followed by an overall best-fit alignment to minimize errors. After superimposition,

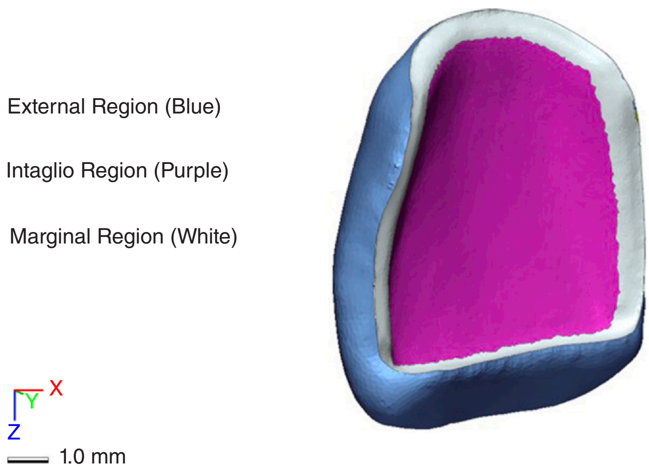

Figure 3. External, intaglio, and marginal surface regions created on reference STL file (RLV-STL). STL, standard tessellation language.

the "3D Compare Tool" of the software program was used to create color-difference maps for the quantitative mean ±standard deviation (SD) evaluation of the 3D deviations between the reference and test STL files. The maximum and minimum deviation values were set to be ±100 µm, and the tolerance range was set at ±10 µm (green).[37] The 3D deviation was analyzed by using the root mean square (RMS) method. A high level of trueness, a high degree of 3D matching between reference and test scans, was obtained when a low RMS was present, according to the International Organization for Standardization (ISO) 5725–2 standard.[38] For each laminate veneer specimen, the RMS values were calculated for 3 different surfaces: external, intaglio, and marginal surfaces. For the external, intaglio, and marginal surfaces, previously segmented regions were selected by using the "Use selected data only" tool, while 3D comparison was done by a single operator (M.E.G.). This 3D analysis was repeated for all laminate veneers, and absolute values of the calculated RMS values (µm) were used for the statistical analyses (Fig. 4).

To evaluate margin quality, laminate veneers were visually examined with a microscope (SMZ445/460 Stereoscopic Zoom Microscope; Nikon Corp) under ×60 magnification by a single operator (D.Y.), who was blinded to the numbering, and a previously reported grading system (grades from 1 to 3) was used.[36] A rough edge, similar to layers, indicated a Grade 1 margin, a slightly rough edge, similar to waves, indicated a Grade 2 margin, and a smooth edge indicated a Grade 3 margin (Fig. 5). Margin quality was examined at each margin (cervical, incisal edge, mesial axial, and distal axial surfaces) of each laminate veneer, and the average was calculated for all specimens.

The normality of data was analyzed by using the Kolmogorov-Smirnov test. Because of the nonnormal

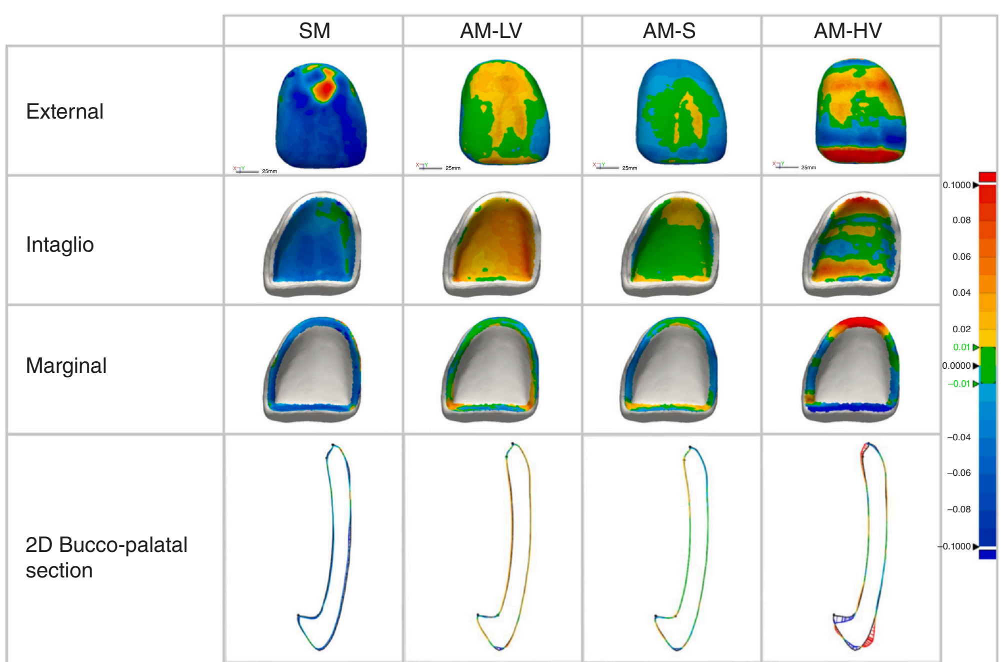

Figure 4. Color maps generated with superimposition of TLV-STLs over RLV-STL for external, intaglio, and marginal surfaces. A 2D buccopalatal section created through middle surface of laminate veneers to illustrate deviations. *Red* color shows overcontoured areas, *blue* color shows undercontoured areas (Nominal values: +100 µm and −100 µm), and *green* color shows acceptable areas within tolerance range (+10 µm and −10 µm). AM-HV, Tera Harz TC-80DP; AM-LV, C&B Permanent; AM-S, Crowntec; RLV-STLs; reference-laminate veneer standard tessellation language (STL) file; SM, Tetric CAD; TLV-STLs; test STL files.

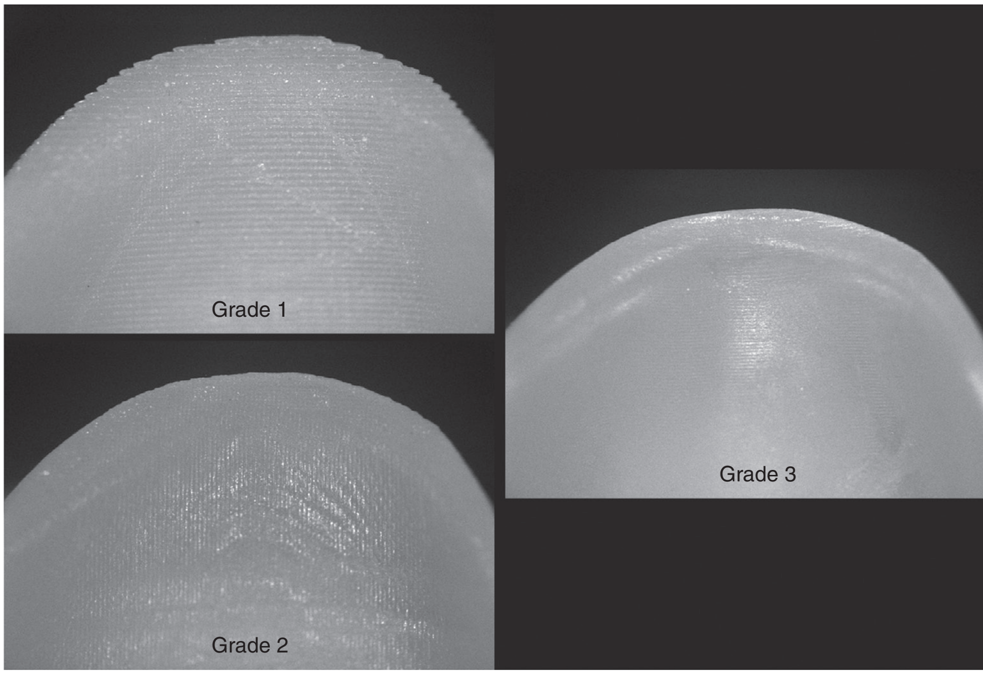

Figure 5. Photographs of cervical margin surface of laminate veneers: cervical margins according to grading system.[36]

distribution, the Kruskal-Wallis and Dunn tests were performed by using a software program (IBM SPSS Statistics, v22.0; IBM Corp) (α=.05). The Mann-Whitney U test was used for pairwise comparisons on each surface.

RESULTS

The Kruskal-Wallis tests revealed significant differences among test groups for all surfaces analyzed (*P*<.001). Table 2 summarizes the descriptive statistics of each material-surface pair. Figure 6 illustrates a boxplot for RMS values.

External, intaglio, and marginal RMS values showed statistically significant differences among test groups (*P*<.001). The SM group had the highest RMS values for the external surface (*P*<.001), whereas the AM-LV group had the lowest RMS values. The AM-HV group had the highest RMS values for the intaglio surface (*P*<.001). The AM-HV group had the highest RMS values for the intaglio surface (*P*<.001), while the AM-S and AM-LV groups had similar

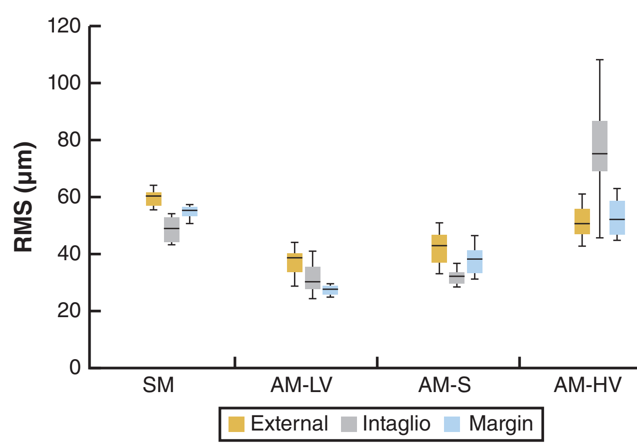

Figure 6. Box plot of root mean square values (µm) for each material-surface pair. AM-HV, Tera Harz TC-80DP; AM-LV, C&B Permanent; AM-S, Crowntec; SM, Tetric CAD.

RMS values (*P*=.955) and lower RMS values than the SM group (*P*<.001). No significant difference was found between the SM and AM-HV groups for marginal RMS

Table 2. Descriptive statistics of RMS values (µm) for each material-surface pair

Material Type	Surface Type					
	External		Intaglio		Marginal	
	Mean ±SD	Median (Min- Max)	Mean ±SD	Median (Min- Max)	Mean ±SD	Median (Min- Max)
SM	59 ±3	60[d] (55–64)	48 ±4	49[b] (43–54)	54 ±2	55[c] (50–57)
AM-LV	37 ±4.3	38[a] (28–44)	31 ±4.9	30[a] (24–41)	27 ±1	27[a] (24–30)
AM-S	42 ±5.2	43[b] (32–51)	32 ±2.4	32[a] (28–36)	38 ±4.6	38[b] (31–46)
AM-HV	51 ±6	50[c] (42–61)	77 ±14	75[c] (45–108)	55 ±12	52[c] (44–93)

AM-HV, Tera Harz TC-80DP; AM-LV, C&B Permanent; AM-S, Crowntec; HV, high-viscosity; LV, low-viscosity; SD, standard deviation; SM, Tetric CAD. Different superscript letters indicate significate differences in columns (*P*<.05).

values, which were higher than for other groups (P=.830). However, the AM-LV group had the lowest RMS values (P<.001). The color deviation maps confirmed that the AM-LV group showed the most favorable pattern at the external and margin surfaces, colored in green or yellow, partly within nominal deviation. A positive deviation was also displayed on the intaglio surface of the AM-LV group. On the contrary, the SM group showed negative deviation in most of the surfaces, and the AM-HV groups showed a mixed pattern of positive and negative deviations. The surface deviation of the AM-S group was within the nominal range at the intaglio surface, but a negative deviation was also displayed at the external surface.

All average values for the axial mesial, axial distal, and incisal edge margin quality of laminate veneers were found to be similar and Grade 3 (smooth edge) in all groups. Notably, when cervical margin quality values were examined, all SM laminate veneers had a Grade 3 rating because of their smooth edges. However, the AM-S and AM-HV groups had a Grade 2 rating and exhibited smoother edges than the AM-LV group, that achieved a Grade 1 rating for cervical margin quality. Within groups, the scores did not vary and did not have any standard deviation. Therefore, groups with different scores were statistically different from each other (P<.001).

DISCUSSION

Significant differences in the fabrication trueness of laminate veneers were found among the AM and SM groups, regardless of the evaluated surface. Compared with the SM, the AM-LV group had better trueness with statistical significance at all surfaces (P<.05). Between the AM groups, the low-viscosity group was better in trueness than the high viscosity group. Between the groups reinforced with glass fillers, the AM group was better in trueness than the SM group on all surfaces. From worst to best, the order of fabrication trueness among the AM and SM groups for each surface was SM < AM-HV < AM-S < AM-LV (external); AM-HV < SM < AM-S < AM-LV (intaglio and margin). Therefore, the null hypotheses were rejected. Furthermore, the AM-LV group showed the smallest surface deviations at the external and margin surfaces, which may lead to minimal adjustment while maintaining adequate structural integrity. On the contrary, the negative deviation (undercontoured) seen with the SM group may indicate additional adjustments (material addition) on every surface of the restoration to compensate for inadequate contouring. Compared with the AM-HV group, the AM-LV and AM-S groups may be more suitable for laminate veneers, considering that their deviation pattern is within the nominal range at the intaglio surface.

The trueness of laminate veneers was higher in the AM-LV or AM-S groups than in the SM group at the external, intaglio, and margin surfaces. Consistent with the present study, Çakmak et al[20] reported that the AM crown with glass-filler reinforced resin, the same resin as the AM-S group, showed better trueness on the occlusal or intaglio occlusal surfaces than the SM composite resin crown. A recent study on the marginal gap of implant-supported crowns by Donmez et al[21] also reported that the AM resin crowns showed significantly better marginal adaptation than the SM resin crowns. Because of the morphological differences between crowns and laminate veneers, the findings may not be directly related to the results of the current study. However, the superiority in trueness of the AM group over the SM group may originate from the different fabrication parameters of 2 manufacturing techniques, such as the minimum layer thickness in 3D-AM and the minimum diameter of milling instruments.[21] For machinable materials such as composite resin or glass-ceramics, undermilling or overmilling on the intaglio or proximal surfaces of the prosthesis may result in a lack of trueness and inadequate adaptation.[26] Although the machined composite resin was reported to show satisfactory dimensional accuracy,[26] the morphology or geometric shape of the laminate veneer may be more suitable for additive manufacturing than milling, and the material of choice was a resin-based material.

Differences in chemical composition or viscosity between the AM groups may have influenced the trueness of the laminate veneers. Among the 3 AM groups, the low-viscosity resin group (AM-LV) had the highest trueness, while the high-viscosity resin group (AM-HV) had the lowest. The AM-LV group was also significantly better in trueness than the AM-S group, which was reinforced with glass filler. These results were consistent with the findings of previous studies.[6,31,39] For vat polymerization processing, such as DLP, resin with a high viscosity because of filler loading or large-size oligomer inclusion can affect the shape-forming and recoating of resin layers during the manufacturing process.[31,39] The viscous behavior of the resin may be affected by the filler surface area or the oligomer functionalization.[39] The dimensional accuracy of the resin for 3D-AM can also be achieved by optimizing these factors.[6,39] Considering the fabrication trueness, the low-viscosity resin (AM-LV) or glass-filler reinforced composite resin (AM-S) might be suggested for the fabrication of definitive resin-based laminate veneers.

In terms of quality analysis of the margin of laminate veneers, the difference was only visually detected in the cervical margin, which displayed rough edges similar to layers in the AM-LV group, while smooth edges were seen in the SM group. The cervical margin quality was the highest with SM laminate veneers, followed by AM-HV, AM-S, and AM-LV. Although the RMS values were reported to be lower in the AM groups, the staircase effect of distinctive layer marks is inevitable with DLP technology, regardless of the type of printable resins. The margin quality evaluation was made only on the cavosurface margin, whereas the RMS was calculated considering the entire margin rather than only the cavosurface margin, including the axial, incisal, and cervical margins. For the SM group, the composite resin has high machinability with less probability of chipping at the thinnest part.[26] If fabrication trueness was not considered the only prerequisite for a restoration, the SM method could be a suitable approach to achieving high manufacturing quality at the thin cervical margin of resin-based laminate veneers.

The preparation design used in this study followed a standard tooth preparation for ceramic laminate veneers. Differences in tooth preparation designs may influence the fabrication's trueness. The authors are unaware of a previous study that examined the trueness of laminate veneers made of 3D-AM resin for definitive use. Therefore, previous studies with which to directly compare the results were unavailable. Other 3D-AM resins indicated for definitive use have been recently introduced, which warrants future investigations. The limitations of the present study included that only 1 build angle was tested. Future studies should investigate the effects of various printing technologies, printing orientations, and materials on the margin quality of laminate veneers made of 3D-AM resin intended for definitive use.

CONCLUSIONS

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

1. Regardless of the evaluated surface, the fabrication technique affected the trueness of laminate veneers.
2. The low-viscosity AM laminate veneers and AM laminate veneers reinforced with glass fillers had higher trueness than SM laminate veneers at all surfaces.
3. The low-viscosity AM laminate veneers had the highest trueness on external and marginal surfaces among test groups.
4. The low-viscosity AM laminate veneers had higher trueness than the high-viscosity AM laminate veneers.

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Deniz Yılmaz: Methodology, Investigation. **Gülce Çakmak**: Conceptualization, Methodology, Investigation, Supervision. **Mehmet Esad Güven**: Formal analysis. **Hyung-In Yoon**: Resources, Writing - original draft. **Martin Schimmel**: Conceptualization, Methodology, Supervision. **Burak Yilmaz**: Conceptualization, Methodology, Supervision, Writing - review and editing.

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