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Research Article

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Posted Date: November 13th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11518683/v1

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Additional Declarations: No competing interests reported.

Layer-Dependent Degradation of Surface-Coated PMMA: Interplay Between Fabrication Method, Simulated Toothbrushing on Surface Roughness and Color Stability

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Abstract

Background: Surface coatings are used to improve the surface and optical properties of provisional restorations, but how the number of coating layers affects their durability across PMMA fabrication methods remains unclear. This in vitro study evaluated the effects of coating-layer number and fabrication method on surface roughness, coating thickness, and color change after simulated toothbrushing.

Methods: Eighty-one PMMA specimens (10 × 10 × 3 mm) were fabricated by milling, 3D printing, or auto-polymerization and coated with one, two, or three layers of Optiglaze Color (n = 9 per subgroup). Surface roughness (Ra), incremental layer thickness, and color (CIELab) were evaluated before and after 10,000 toothbrushing cycles, and coating cross-sections were examined by scanning electron microscopy (SEM). Data were analyzed using ANOVA (α = 0.05).

Results: Baseline Ra was highest in auto-polymerized (2.50 ± 0.74 μm), intermediate in 3D-printed (1.36 ± 0.35 μm), and lowest in milled (0.70 ± 0.33 μm) specimens. SEM showed that cumulative coating thickness increased from approximately 100 to 200 μm with additional layers. Coating application reduced Ra in all groups except the one-layer milled group. After brushing, Ra increased significantly in most groups, most markedly in the one- and two-layer milled groups, whereas the three-layer coating maintained the lowest Ra values. Thickness of

the C Plus and Clear HV layers decreased significantly in the milled and auto-polymerized groups but not in the 3D-printed group. Δ*E** remained ≤ 3.3 except in the three-layer 3D-printed and auto-polymerized groups, and coating-layer number, but not fabrication method, significantly affected Δ*E**.

Conclusions: Within the limitations of this in vitro study, multilayer coatings were associated with lower Ra after toothbrushing than the single-layer coating, although Ra still increased significantly in several multilayer groups. Thickness loss varied according to the fabrication method and layer, and the three-layer coating exceeded the acceptable color threshold in two methods. The benefit of additional layers should be weighed against both surface durability and color stability.

Keywords: Polymethyl methacrylate; Surface coating; Toothbrushing; Surface roughness; Color stability

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Introduction

Provisional restorations serve as an essential transitional phase in dental treatment, providing biological protection, maintaining occlusal and functional stability, guiding soft tissue architecture, and acting as a diagnostic prototype for evaluating esthetic, phonetic, and functional outcomes prior to definitive prosthesis placement [1]. Surface integrity plays a significant role in the clinical performance of these restorations, influencing aesthetics [2,3],

plaque accumulation [4], and gingival health [5,6]. To optimize surface integrity in clinical settings, various polishing protocols and surface coating systems, such as Optiglaze Color®, have been introduced [7-9].

Polymethyl methacrylate (PMMA) has long been used for the fabrication of provisional prostheses due to its affordability and ease of use. Recently, modern techniques such as computer-aided design and computer-aided manufacturing (CAD/CAM) technology have been utilized to fabricate interim restorations. Additive manufacturing (3D printing) via photopolymerization of liquid resin [10] and subtractive processes involving precision milling from pre-formed PMMA blocks or blanks have enhanced manufacturing precision and mechanical properties [11]. In contrast, the traditional method of powder-liquid auto-polymerized PMMA remains widely used because of its cost-effectiveness and simplicity. Each fabrication method imparts different surface characteristics to the material, particularly in surface roughness. Fiore et al. [12] compared the flexural property and surface roughness of heat-polymerized, CAD-CAM milled, and 3D-printed PMMA, they found CAD group displayed the best flexural property and lowest roughness before polishing, but all tested PMMAs had similar surface roughness after polishing. Although different manufacturers were involved, previous studies have also supported that the roughness of CAD/CAM PMMA is lower than that of conventional heat-polymerized PMMA [13,14,15]. The surface roughness values of the base materials fabricated using the 3D printing method were higher compared to

those fabricated with milled and heat-polymerized PMMA resin, both before and after polishing [16].

Surface coating and polishing are fundamentally different, traditional polishing procedures are used to alter and smooth the "original" surface of the material through mechanical grinding (e.g. using silicon carbide sandpaper, eraser polishing heads, or pumice stones). In contrast, surface coating (or glaze) is an additive process in which a new layer of surface sealant or glaze material is applied directly to the top layer of the restoration. The application of coating creates a new interface. When surface coatings are used, the low-viscosity monomers (such as methyl methacrylate) can cover and penetrate into the tiny cracks and surface defects left over from the polishing process, sealing the surface and creating a new interface with different physical and chemical properties. However, this newly established interface is usually softer than the underlying substrate material, which not only changes the hydrophilicity and surface free energy of the surface, but also poses the risk of debonding or wear over time. The thickness and layers of the coating are crucial for its protective effect. Studies have shown that in order to achieve the desired optical and surface properties, the thickness of the coating must be precisely controlled (e.g., applying a 100-μm thick layer of external stain and glaze). Under long-term simulated toothbrushing and mechanical friction, the thin coating will gradually wear away over time, causing its barrier effect as a barrier against moisture absorption and pigment penetration to fail. Once the coating is lost due to mechanical wear or clinical

regrinding, the underlying PMMA material is directly exposed to the oral environment, which will significantly affect the long-term optical stability and surface resistance of the restoration. Surface coating systems, such as Optiglaze Color®, do not merely smooth the surface but create an additional polymeric layer that alters the surface–environment interaction. The integrity of this coating layer, including its thickness and layering strategy, may play a critical role in determining long-term surface and optical stability. In addition, a recent study by Azpiazu-Flores et al. [17] has also pointed out that the uniformity or number of layers of the Optiglaze coating may also be a factor affecting material properties.

Toothbrushing plays a critical role in oral hygiene; however, it can also have negative effects on restorative materials. Toothbrush bristles can cause uneven wear on polished or sealant-treated surfaces, leading to increased surface roughness [18-20]. Under repetitive toothbrushing and coloring challenges, these coatings may undergo progressive degradation, including mechanical coating wear, layer delamination, and potential exposure of the underlying substrate, thereby altering both surface roughness and color stability. This abrasion can cause significant aesthetic and biological disadvantages, such as reduced gloss, discoloration, and the accumulation of dental plaque [18,21,22]. Additionally, surface sealants may be worn off under prolonged brushing, further affecting the material performance [21].

While previous studies have evaluated the effects of fabrication methods, polishing, and brushing on PMMA materials, limited evidence exists regarding how layer-dependent coating strategies interact with fabrication methods under combined mechanical and color stability following toothbrushing. Therefore, this study aimed to investigate the layer-dependent degradation behavior of surface-coated PMMA fabricated by different methods, with a focus on the interplay between coating layers, simulated toothbrushing, and coloring in determining surface roughness, coating thickness and color stability.

Materials and methods

Sample preparation

A total of 81 rectangular specimens (10 × 10 × 3 mm) were prepared from three different fabrication methods: milling, 3D printing, and auto-polymerizing. Milled specimens were fabricated with a 5-axis dental milling machine (SYI-DN, Marketech International Corp., USA) from PMMA discs (PMMA Disk; Yamahachi Dental Co., Japan & Telio®CAD). 3D-printed specimens were produced by a digital light processing 3D printer (XL4K, Phrozen Technology, Hsinchu, Taiwan) and light-polymerizing resin (AA Temp, Enlighten Materials, Taipei, Taiwan). Auto-polymerized PMMA (Tokuso CureFast, Tokuyama, Tokyo, Japan) specimens were fabricated according to the manufacturer's recommendations using putty molds (Aquasil Putty, Dentsply Sirona, USA).

The PMMA specimens' surface coloring process was performed by coating OPTIGLAZE Color® (OPTIGLAZETM Color, GC, America) according to the manufacturer's protocol. Each type of PMMA specimen was divided into three subgroups (n = 9 per subgroup), corresponding to the number of applied layers: One-layer group: Clear layer only; Two-layer group: Clear + C Plus layers; Three-layer group: Clear + C Plus + Clear HV layers. A standardized brushing method using a 10-mm-wide bristle brush was implemented for uniform application.

To evaluate the durability of the colored surfaces, all specimens were subjected to a toothbrushing simulation. The toothbrushing test was performed using an abrasion machine (PAT-2012, PROES Co., Taichung, Taiwan) under the following conditions: 10,000 brushing cycles at a rate of 60 cycles per minute and stroke length of 40 mm. The test pieces were soaked in deionized water, without toothpaste as a medium.

Sample characterization

The surface roughness values (Ra, μm) were measured using a profilometer contact surface measurement device (SurfTest SJ-310, Mitutoyo, Tokyo, Japan) with six tracings taken from different locations on each specimen, and the mean value was used as the representative roughness value for statistical analysis. The surface roughness of the untreated raw sample was denoted as $R_{a,0}$. After the coloring and brushing tests, the surface roughness was recorded again and marked as $R_{a,1}$ and $R_{a,2}$, respectively.

Coating thickness was evaluated sequentially to determine the thickness of each individual coating layer. For the one-layer specimens, the thickness of the first coating layer was measured directly. For the two-layer specimens, the total coating thickness after application of the second layer was measured, and the thickness of the second layer was calculated by subtracting the corresponding one-layer thickness from the cumulative thickness. Similarly, for the three-layer specimens, the thickness of the third layer was calculated by subtracting the cumulative thickness of the two-layer coating from the cumulative thickness of the three-layer coating. Thus, the reported values for the one-, two-, and three-layer groups represent the thicknesses of the individual coating layers rather than the cumulative thickness of the entire coating system. For each specimen, coating thickness was measured by using a digital optical microscope (BX51; Olympus Corp., Tokyo, Japan), and the mean value was calculated for statistical analysis. The obtained thickness at this stage was denoted as T_1. Scanning electron microscopy (SEM) was performed to visualize the cumulative thickness and morphology of the coating system. Representative specimens from the one-, two-, and three-layer coating groups were sectioned to expose the coating–substrate cross-section. The specimens were positioned at an oblique angle relative to the electron beam to allow visualization of the coating layer in cross-section. SEM observations were performed using a field-emission scanning electron microscope (FE-SEM; JSM-7001F, JEOL Ltd., Tokyo,

Japan). Additionally, color measurements, including *L**, *a**, and *b** values, were obtained using a digital spectrophotometer (Vita Easyshade V; VITA North America).

After the brushing test, thickness, and color parameters were reassessed for all specimens. The reassessed thickness at this stage was denoted as T_2. Comparisons were made between pre- and post-brushing values to evaluate changes in material properties. Color stability was evaluated using the CIELab system and a digital spectrophotometer (Vita Easyshade V; VITA North America) before and after toothbrushing. Calibrations were performed following manufacturer's instructions before testing. Specimens were all tested under the same environmental conditions with similar lighting conditions and humidity. Each specimen was measured 3 times over the same background.

The coordinate *L** represented lightness, while *a** and *b** corresponded to the red-green and yellow-blue axes, respectively. Color difference (Δ*E**) was calculated using the formula:

$$\Delta E^* = \sqrt{\{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2\}}$$

where ΔL*, Δa*, and Δb* are the differences of L*, a*, and b* color parameters before and after a brushing test.

Statistical analysis

All statistical analyses were performed using IBM SPSS Statistics for Windows, Version 20 (IBM Corp., Armonk, NY, USA). One-way analysis of variance (ANOVA), followed by Tukey's honestly significant difference (HSD) post hoc test, was used to

compare the mean values among the experimental groups. Changes in each group before and after toothbrushing were analyzed using paired t-tests. To evaluate the influence of manufacturing methods and coating layers on color difference (ΔE^*), a two-way ANOVA was performed to assess the main effects of each factor and their interaction. In addition, to evaluate changes in surface roughness and coating thickness, a three-factor mixed repeated-measures ANOVA was performed. Fabrication method (milled, 3D-printed, and auto-polymerized) and coating-layer number (one-, two-, and three-layer) were treated as between-subject factors, whereas brushing stage (before and after toothbrushing) was treated as the within-subject factor. Main effects and interaction effects among the three factors were analyzed. Statistical significance was set at $p < 0.05$.

Results

Representative OM images of coated PMMA specimens are shown in Figure 1. Distinct baseline surface characteristics were observed among the three PMMA fabrication methods prior to coating application. The 3D-printed PMMA specimens exhibited characteristic layered patterns associated with the additive manufacturing process, whereas the auto-polymerized PMMA specimens showed numerous small pores distributed across the surface. In contrast, the milled PMMA specimens demonstrated relatively smoother and more homogeneous surface morphologies. In addition, differences in coating morphology and apparent surface coverage were observed among the different coating-layer configurations. Specimens with

multiple coating applications generally exhibited more continuous and thicker coating layers compared with one-layer specimens across all fabrication methods. Representative cross-sectional SEM images of the specimens with one, two, and three coating layers are shown in Fig. 2. The one-layer coating (Clear) had a thickness of approximately 100 μm, and discontinuities were observed along the interface. In the two-layer coating (Clear + C plus), the cumulative thickness increased to approximately 170 μm. Although the C plus layer was more continuous than the Clear layer, a few voids remained within it. In the three-layer coating (Clear + C plus + Clear HV), the cumulative thickness reached approximately 200 μm, and the outermost Clear HV layer showed a relatively continuous and uniform distribution without noticeable defects. The SEM images demonstrated the cumulative coating structure formed by successive coating applications. The cumulative coating thickness increased with the number of coating applications.

The pooled baseline surface roughness ($Ra_{,0}$) values of PMMA specimens fabricated using three different methods are summarized in Table 1. When all coating-layer groups were combined, auto-polymerized specimens exhibited the highest surface roughness (2.50 ± 0.74 μm), followed by 3D-printed specimens (1.36 ± 0.35 μm), whereas milled specimens demonstrated the lowest roughness values (0.70 ± 0.33 μm). Figure 3 shows the surface roughness of PMMA fabricated by three different manufacturing methods at three distinct stages: initial state ($Ra_{,0}$), after coating application ($Ra_{,1}$), and after the toothbrushing test ($Ra_{,2}$).

The effects of the number of coating layers (one-, two-, and three-layer) were also evaluated. At the initial stage, the auto-polymerized PMMA exhibited the highest roughness (2.26–2.64 μm), followed by the 3D-printed group (1.17–1.36 μm), while the milled PMMA presented the smoothest initial surface (0.56－0.81 μm). Upon the application of the coating, a significant reduction in roughness was observed across almost all groups ($P < 0.05$), except for the one-layer milled group ($P = 0.723$). Following simulated toothbrushing, Ra increased in most groups relative to the post-coating values ($Ra_{,1}$). Increases in $Ra_{,2}$ were statistically significant in most groups (all $P < 0.05$), with the one-layer and two-layer milled group reaching approximately 1.55 μm and 1.02 μm, respectively. In contrast, the three-layer milled group and the one- and three-layer auto-polymerized groups exhibited smaller increases in $Ra_{,2}$, with no statistically significant differences. Within each fabrication method, the three-layer groups had the lowest $Ra_{,2}$ (0.50–0.69 μm in the milled and 3D-printed groups; 0.74 μm in the auto-polymerized group). Overall, $Ra_{,2}$ of the auto-polymerized subgroups remained higher than in the corresponding milled and 3D-printed subgroups.

The incremental thickness of each coating layer before (T_1) and after (T_2) toothbrushing simulation is presented in Fig. 4. Each colored segment represents the thickness of the corresponding layer, and the total stacked bar height represents the cumulative thickness of the three-layer coating. For the three-layer configuration, the cumulative coating thickness, calculated as the sum of the incremental thicknesses of the three individual layers, ranged from

approximately 150 to 185 μm across the fabrication methods before toothbrushing. These values represent the total thickness of the multilayer coating rather than the thickness of any single layer. After brushing, incremental thickness decreased numerically in all groups; however, the magnitude and statistical significance of the reduction varied according to the fabrication method and coating configuration. In the 3D-printed group, thickness decreased non-significantly across all layers (all $P > 0.05$). In the milled group, the incremental thickness of the Clear, C Plus, and Clear HV layers decreased from 83.59 ± 27.24 to 79.38 ± 29.55 μm, 45.51 ± 11.40 to 23.34 ± 10.88 μm, and 22.24 ± 4.82 to 13.12 ± 3.68 μm, respectively; the reduction was not significant for the Clear layer ($P > 0.05$), but significant for the C Plus and Clear HV layers ($P < 0.05$). In the auto-polymerized group, the Clear layer slightly decreased from 106.59 ± 27.08 to 92.22 ± 40.98 μm ($P > 0.05$), whereas the C Plus and Clear HV layers decreased significantly from 51.80 ± 13.16 to 37.93 ± 11.06 μm and from 24.65 ± 7.38 to 15.27 ± 5.15 μm, respectively ($P < 0.05$).

Color changes (ΔE^*, ΔL^*, Δa^*, and Δb^*) after toothbrushing simulation are presented in Figure 5. The radar plots revealed distinct color-change profiles among the different fabrication methods and coating-layer configurations. Auto-polymerized specimens generally exhibited larger radar areas, indicating greater overall color variation after toothbrushing simulation, whereas milled specimens demonstrated more compact profiles, suggesting superior color stability. Variations in the radar shape reflected differences in the contributions of ΔL^*, Δa^*,

and Δ*b** to the overall color change (Δ*E**). In the 3-layer 3D-printed and auto-polymerized groups, color differences exceeding the selected clinical acceptability threshold (Δ*E** > 3.3) were primarily driven by a substantial shift in Δ*L** and Δ*b** axes, these findings indicate differences in the color-change profiles among groups; however, the underlying mechanisms could not be determined from the color measurements alone.

Two-way ANOVA (Table 2) demonstrated that coating-layer number significantly affected Δ*E** (F = 5.07, *P* = 0.02), while the fabrication method had no significant effect (F = 1.91, *P* = 0.18). Moreover, no significant interaction was observed between fabrication method and coating-layer configuration (F = 1.54, *P* = 0.23).

The mixed-design repeated-measures ANOVA (Table 3) showed significant main effects of fabrication method, coating-layer number, and toothbrushing on Ra (all P < 0.001). Significant two-way interactions were found for method × layer (F = 26.58, P < 0.001), toothbrushing × method (F = 8.66, P < 0.001), and toothbrushing × layer (F = 6.18, P = 0.003). A significant three-way interaction (F = 4.45, P = 0.003) indicated that the effect of toothbrushing differed according to both the fabrication method and the number of coating layers. Toothbrushing significantly reduced layer thickness overall (F = 124.29, P < 0.001), and the reduction varied according to layer (P = 0.003) and to the combination of fabrication method and layer (three-way interaction, F = 6.46, P < 0.001; Table 4).

Discussion

The present study demonstrated that the performance of surface-coated PMMA is governed not only by the fabrication method but also by the integrity of the coating layer. More importantly, coating-layer configuration significantly influenced the degradation behavior during toothbrushing, thereby affecting surface roughness, coating thickness, and color stability. Optiglaze Color® significantly reduced surface roughness in all groups except the one-layer milled group, consistent with a previous report on glaze materials [23]. However, the degree of improvement varied depending on the fabrication method and the number of coating layers.

Auto-polymerized PMMA exhibited the highest roughness, likely due to the inherent irregularities in the chemical self-polymerization process. Similar results were observed in other studies, which attributed the higher roughness of auto-polymerized PMMA to porosity caused by air entrapment during the polymerization process [24]. In contrast, milled PMMA showed the lowest initial roughness, attributed to the precise mechanical cutting process that produces smoother surfaces. The intermediate Ra in 3D-printed specimens because the layer-by-layer fabrication technique, which tends to leave visible stratifications [25].

Previous studies have demonstrated the positive effect of surface sealant or glaze materials on surface roughness [3,25-28]. Sealant agents fill the microdefects and microfissure and improve the surface roughness. The application of Optiglaze Color® established a new polymeric interface possessing different mechanical and tribological properties rather than

merely smoothing the substrate. After the application of the first (Clear) layer, surface roughness decreased significantly in all groups except the one-layer milled group, suggesting that even a single layer of Optiglaze Color® can smooth the surface of most PMMA substrates. This may be related to the low viscosity of the material, which allows it to flow into surface irregularities and level the substrate topography [29], and to the relatively large thickness of the Clear layer observed in this study (Fig. 4).

The milled group had the lowest baseline Ra (0.56–0.81 μm), and the one-layer coating did not significantly reduce its roughness. Because the milled substrate was already relatively smooth, there may have been limited room for further improvement from a single layer. In contrast, the auto-polymerized group showed the highest Ra both before and after coating compared with the other two groups (Fig. 3). This is likely related to the porosity and irregularities produced by air entrapment during polymerization [24]. Although the coating reduced the roughness of this group, presumably by filling surface pores and irregularities, the residual roughness remained higher than that of the other two groups, particularly when only one layer was applied. This suggests that a single layer may be insufficient to fully level the highly irregular surface of auto-polymerized PMMA, and that the initial surface condition of the substrate can limit the smoothing effect of the coating.

The effects of simulated toothbrushing on surface roughness varied according to the PMMA fabrication method and coating-layer configuration. Ra increased significantly in most groups,

with the largest increases observed in the one- and two-layer milled subgroups. In the one-layer groups, the Clear layer was directly exposed to brushing, whereas the outermost layer was C Plus in the two-layer configuration and Clear HV in the three-layer configuration. Thus, differences in Ra changes may be associated with the outermost coating material and/or the multilayer configuration; however, their individual contributions could not be distinguished in the present study. Notably, the measured thickness of the Clear layer did not decrease significantly after brushing, despite the significant increase in Ra in the one-layer milled and 3D-printed groups. This finding indicates that changes in surface roughness were not necessarily accompanied by measurable reductions in coating thickness. Moreover, Ra and coating thickness did not exhibit consistent patterns of change across all groups. For example, the measured thickness associated with the Clear HV layer decreased significantly in the auto-polymerized group, whereas Ra in the three-layer subgroup did not change significantly. Therefore, the present findings do not establish a direct relationship between these parameters or confirm a common degradation mechanism.

Regarding coating thickness, significant reductions in the measured thicknesses associated with the C Plus and Clear HV layers were observed after brushing in the milled and auto-polymerized groups, whereas no statistically significant reduction was detected in the 3D-printed group. Although numerical decreases were observed in the 3D-printed group, these changes did not reach statistical significance and should not be interpreted as evidence of

superior wear resistance. Myagmar et al. [30] reported lower wear-volume loss in 3D-printed than in milled PMMA after chewing simulation without a surface sealant. This finding provides relevant background for interpreting the lack of a significant thickness reduction in the present 3D-printed group, although differences in the test conditions and outcome measures preclude direct comparison. The previous studies [31,32] evaluated uncoated PMMA under chewing simulation, whereas the present study examined coated surfaces subjected to toothbrushing. Differences in loading conditions and in the surface exposed to abrasion may also contribute to the different findings. Because post-brushing coating morphology was not examined, the mechanisms underlying the observed thickness changes remain unclear. Further studies incorporating post-brushing cross-sectional microscopy and direct wear measurements are needed to determine whether the observed thickness changes are associated with coating loss or other alterations in coating integrity, and how these changes vary among different PMMA substrates and coating configurations.

The digital spectrophotometer (Vita Easyshade V) used in this study has a limited ability to determine the absolute color coordinates values. However, it is a reliable instrument for assessing color changes in clinical and research settings [33]. The ΔE* values indicate the color changes of the interim prostheses after simulated toothbrushing. When ΔE* is less than 1, it is considered visually imperceptible. When the ΔE* is between the range of 1 to 3.3, it is considered that the color change is clinically acceptable and can only be detected by skilled

individuals. When the ΔE^* is larger than 3.3, the color change is considered clinically unacceptable and can be easily observed by laypeople [34]. In the present study, the ΔE^* values of different fabricated methods were all between the clinical acceptable range of 1 to 3.3, except for the three-layer in 3D-printed and auto-polymerized group.

In this in vitro model, changes in surface roughness, coating thickness, and color did not follow a uniform pattern across groups. For example, the Clear layer showed no significant thickness loss after toothbrushing, yet Ra increased significantly in the one-layer 3D-printed and milled groups, whereas the C Plus and Clear HV layers of the auto-polymerized group decreased significantly in thickness without a significant increase in Ra in the three-layer subgroup. Likewise, the three-layer 3D-printed group showed no significant thickness reduction but exceeded the clinically acceptable color threshold ($\Delta E^* > 3.3$). Within the limitations of this study, multilayer coatings were associated with lower Ra after simulated toothbrushing, although Ra still increased significantly in several multilayer groups. In addition, thickness loss differed according to the fabrication method, and color change was affected by the number of layers, with the three-layer coatings exceeding the acceptable threshold in two of the three fabrication methods. Therefore, the potential benefits of applying additional coating layers should be evaluated in terms of both surface durability and color stability, rather than assuming that increasing the number of layers will consistently improve all aspects of performance.

The limitation of the present study included that the toothbrushing simulation did not duplicate the condition in oral environment, which materials are exposed to higher temperature and saliva containing various proteins and enzymes. The use of harder brush and different direction movement could also have influenced the results. Additionally, the absence of detailed information on the Optiglaze Color® composition restricts the ability to assess its specific effects on surface characteristics and wear resistance. Furthermore, the PMMA materials in this study were unpolished, unlike clinical practice where polishing is standard. This may affect wear resistance and surface properties. Future investigation should assess the impact of polishing and more precise intraoral simulation to evaluate the effect of these factors.

Conclusion

Within the limitations of this in vitro study, multilayer coatings were associated with lower Ra after simulated toothbrushing than the single-layer coating, although Ra still increased significantly in several multilayer groups. In addition, coating thickness loss differed according to the PMMA fabrication method, and the three-layer coating in the 3D-printed and auto-polymerized groups exceeded the clinically acceptable color change threshold ($\Delta E^* > 3.3$). Therefore, the benefit of additional coating layers should be weighed against both surface durability and color stability, rather than assuming that more layers improve all aspects of performance. These findings may serve as a foundation for optimizing future surface coating systems and improving the durability of provisional prosthetic materials.

Acknowledgements The authors also appreciate assistance from Core Facility Center (National Cheng Kung University, Taiwan) in operating the SEM instrument.

Funding This study was supported partly by a grant from the Kaohsiung Medical University Hospital (KMUH111-1R71) and grants from National Science and Technology Council, Taiwan (NSTC114-2314-B-037-028).

Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable. This in vitro study did not involve human participants, human data, human tissue, or animals; therefore, ethics approval and consent were not required.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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Figure captions

Figure 1. OM images (10× magnification) of coated PMMA specimens fabricated by different methods and treated with different coating-layer configurations.

Figure 2. Representative cross-sectional SEM images of specimens with different coating layers: one-layer (Clear), two-layer (Clear + C plus), and three-layer (Clear + C plus + Clear HV). Yellow arrows indicate the interfaces between adjacent coating layers. The images illustrate the cumulative coating thickness and cross-sectional morphology produced by successive coating applications

Figure 3. Surface roughness evolution of PMMA specimens fabricated by different methods before coating ($R_{a,0}$), after coating application ($R_{a,1}$), and after toothbrushing simulation ($R_{a,2}$).

Figure 4. Incremental thickness of the coating layers before and after toothbrushing simulation in specimens fabricated by 3D printing, milling, and auto-polymerization. Each colored segment represents the thickness of the corresponding layer (Clear, C Plus, Clear HV), and the total stacked bar height represents the cumulative coating thickness.

Figure 5. Radar plots showing color stability profiles (ΔL^*, Δa^*, Δb^*, and ΔE^*) of PMMA specimens fabricated by different methods and coated with one, two, or three layers of Optiglaze Color® after toothbrushing simulation.

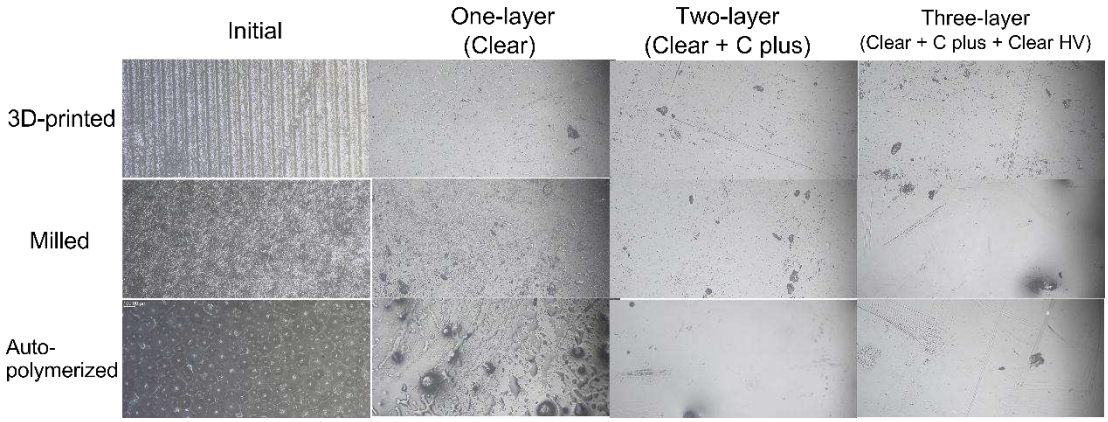

Initial
One-layer
(Clear)
Two-layer
(Clear + C plus)
Three-layer
(Clear + C plus + Clear HV)
3D-printed
Milled
Auto-
polymerized

Figure 1

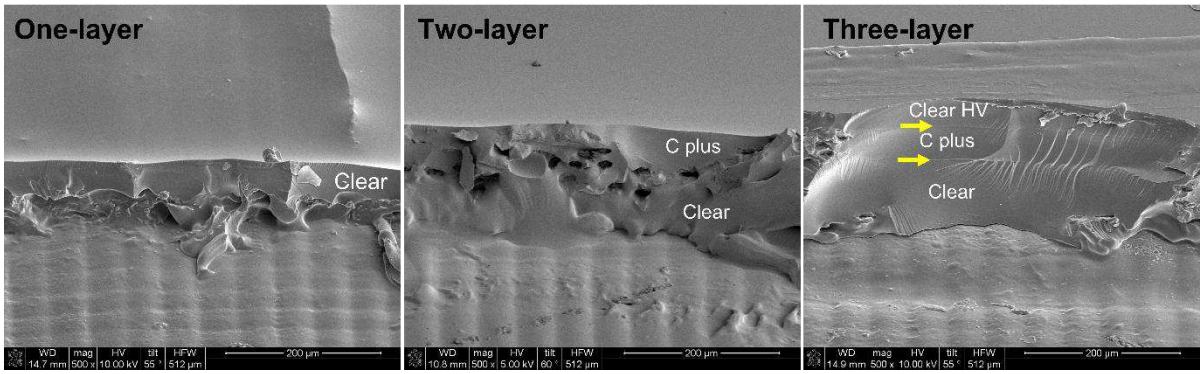

One-layer
Clear
Two-layer
C plus
Clear
Three-layer
Clear HV
C plus
Clear

Figure 2

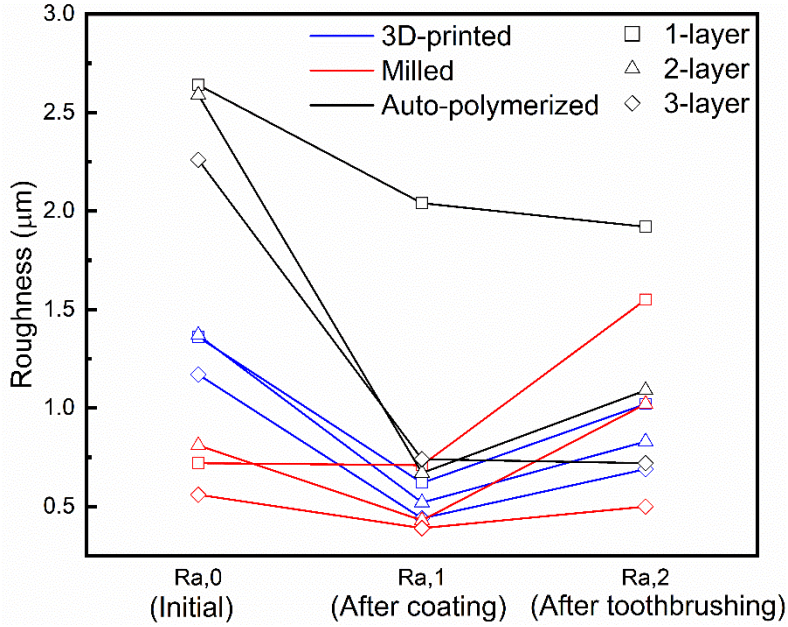

3.0
2.5
2.0
1.5
1.0
0.5
Roughness (μm)
3D-printed
Milled
Auto-polymerized
1-layer
2-layer
3-layer
Ra,0
(Initial)
Ra,1
(After coating)
Ra,2
(After toothbrushing)

Figure 3

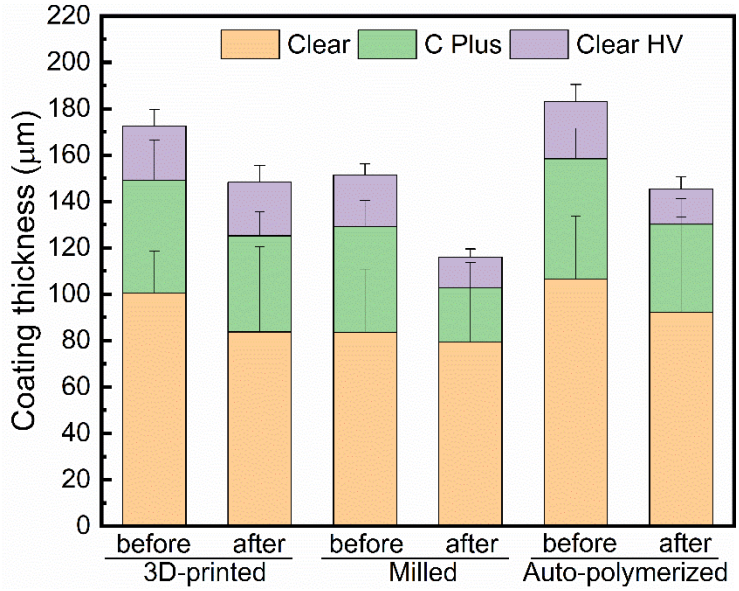

Clear
C Plus
Clear HV
Coating thickness (µm)
220
200
180
160
140
120
100
80
60
40
20
0
before
after
before
after
before
after
3D-printed
Milled
Auto-polymerized

Figure 4

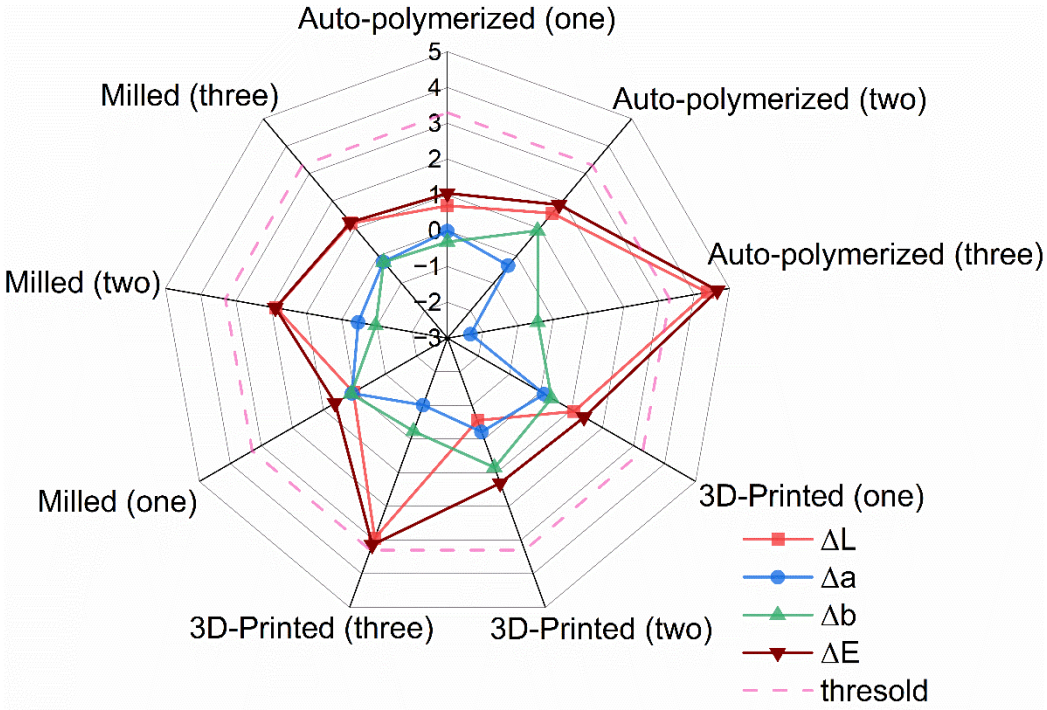

Auto-polymerized (one)
Auto-polymerized (two)
Auto-polymerized (three)
3D-Printed (one)
3D-Printed (two)
3D-Printed (three)
Milled (one)
Milled (two)
Milled (three)
5
4
3
2
1
0
−1
−2
−3
ΔL
Δa
Δb
ΔE
thresold

Figure 5

Table 1. Pooled baseline surface roughness ($R_{a,0}$; μm) values of PMMA specimens fabricated using different methods.

Fabrication method	Mean	SD	*P*-value
3D Printed	1.36	0.35	
Milled	0.70	0.33	< 0.001
Auto-Polymerized	2.50	0.74	

Table 2. Two-way ANOVA examining the main effects of fabrication method and coating-layer number and their interaction on color difference.

Term	DF	Sum of Squares	Mean Square	F	P-value
Method	2	10.05	5.02	8.60	< 0.001
Layer	2	26.64	13.32	22.79	< 0.001
Method × Layer	4	16.22	4.05	6.93	< 0.001
Error	72	42.09	0.58		
Total	80	94.99			

Table 3. Mixed-design repeated-measures ANOVA of surface roughness before ($Ra_{,1}$) and after ($Ra_{,2}$) toothbrushing.

Source	DF	Sum of Squares	Mean Square	F	P-value	Partial η^2
Between-subjects						
Method	2	8.311	4.156	72.07	< 0.001	0.667
Layer	2	15.958	7.979	138.39	< 0.001	0.794
Method × Layer	4	6.130	1.533	26.58	< 0.001	0.596
Error	72	4.151	0.058			
Within-subjects						
Toothbrushing	1	3.918	3.918	59.27	< 0.001	0.452
Toothbrushing * Method	2	1.145	0.572	8.66	< 0.001	0.194
Toothbrushing * Layer	2	0.818	0.409	6.18	0.003	0.147
Toothbrushing * Method * Layer	4	1.176	0.294	4.45	0.003	0.198
Error	72	4.760	0.066			

Table 4. Mixed-design repeated-measures ANOVA of incremental layer thickness before (T_1) and after (T_2) toothbrushing.

Source	DF	Sum of Squares	Mean Square	F	P-value	Partial η^2
Between-subjects						
Method	2	3342.840	1671.420	2.53	0.087	0.066
Layer	2	142268.369	71134.185	107.71	< 0.001	0.749
Method × Layer	4	1190.420	297.605	0.45	0.772	0.024
Error	72	47552.399	660.450			
Within-subjects						
Toothbrushing	1	4740.429	4740.429	124.29	< 0.001	0.633
Toothbrushing * Method	2	154.766	77.383	2.03	0.139	0.053
Toothbrushing * Layer	2	469.582	234.791	6.16	0.003	0.146
Toothbrushing * Method * Layer	4	984.778	246.195	6.46	< 0.001	0.264
Error	72	2746.078	38.140			