

COMPARATIVE WEAR ANALYSIS OF CONVENTIONAL VERSUS CAD/CAM COMPOSITE VENEERED PEEK CROWNS USING 3D SURFACE DEVIATION

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ABSTRACT

Purpose: Due to a lack of data on their wear behavior, the study aimed to analyze the two-body wear rate of two different composite veneered computer-aided design/computer-aided manufacturing (CAD/CAM) polyetheretherketone (PEEK) posterior crowns after wear simulation using 3D surface deviation.

Materials and Methods: Twenty duplicated epoxy resin models of prepared mandibular first molar to receive an all-ceramic crown were fabricated. Twenty CAD/CAM PEEK substructures were manufactured and divided according to the veneering technique into two groups (n=10); group (H): CAD/CAM High Impact Polymer Composite (HIPC) veneered PEEK substructures, and group (C): Conventional Crea.lign composite veneered PEEK substructures (control). The specimens underwent thermal and mechanical loading (49N, 5/55°C; 120,000 chewing cycles) as antagonized by steatite ceramic balls. 3D surface deviation analysis using a 3D dental scanner and Geomagic Design X software was applied before and after chewing simulation to determine the volumetric wear loss (mm³). Data were statistically analyzed with the Mann-Whitney U test to compare the two groups. The significance level was set at p≤0.05.

Results: H group (-0.0398 [-0.0913- -0.0042] mm³) showed statistically significant lower median volumetric wear loss than C group (0.1195 [0.0233-0.233] mm³) (P-value=0.050, Effect size=2.928).

Conclusions: HIPC veneered PEEK crowns showed lower volumetric wear loss than Crea.lign veneered PEEK crowns

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INTRODUCTION

Wear resistance is a fundamental feature for everyday dental material's functioning. To predict the longevity of restorative materials, *in vitro* studies provided primary evidence about their mechanical behavior.¹⁻³

As no specific evaluating technique for the surfaces of dental materials is used, a protocol to assess the wear manner in three dimensions (3D) is demanded.^{1,4} The mostly utilized qualitative and quantitative descriptions of the dental form are topographical and 3D surface deviation analyses.⁵⁻⁸ 3D surface deviation analysis is a non-destructive methodology that numerically and visually represents its result.^{9,10} It works by allowing superimposition analysis of measured and reference data. The trueness of extracted data, known as the closeness of agreement between the measurement and actual values, can be assessed using an optical scanner and 3D inspection software.⁸⁻¹¹

Polyetheretherketone (PEEK) represents a potential alternative material in fixed and removable prosthetic dentistry. It shows adequate mechanical stability in the restorative field.¹² However, the poor translucency and greyish or even white color of PEEK precludes its usage as a monolithic aesthetic restoration. Therefore, further veneering ceramic materials or composite resins are still necessary, as PEEK allows an efficient bonding to veneering materials.¹³⁻¹⁴ Computer-aided design/computer-aided manufacturing (CAD/CAM) veneering is one of the veneering methods. High Impact Polymer Composite (HIPC) represents a digital veneering material that is an amorphous, cross-linked, and micro-ceramic-filled composite with superior physical properties to conventional polymethyl methacrylate (PMMA). It has a 2200 MPa elastic modulus and a flexural strength of >120 MPa. Because HIPC has been studied *in vivo* and accepted for over 7 years, it is recommended for a long-term dental prosthetic restoration.¹⁵ Moreover,

as a high-performance polymer, HIPC maintains its strength compared to ceramic (ceramic "ages").¹⁶ Additionally, conventional PEEK substructure veneering with light polymerized composite resin is commonly used. Crea.lign conventional composite contains 50 % opalescent ceramic nanofillers and an oligomer matrix that adapt its mechanical properties to various substructure materials as claimed by the manufacturer. Besides, pre-fabricated veneers (e.g., visio.lign) are also considered.

The study aimed to compare two-body wear rates of two different composite veneered PEEK posterior crowns using 3D surface deviation analysis. The hypothesis was that the tested CAD/CAM HIPC veneered PEEK crowns would outperform conventional Crea.lign composite veneered PEEK crowns in terms of wear resistance.

MATERIALS AND METHODS

In the present study, wear loss was used as the primary outcome for power analysis. The mean standard deviation (SD) values for the HIPC and Crea.lign composite veneered PEEK crown groups were -0.0048 (0.0155) mm³ and 0.0187 (0.0025) mm³, respectively, based on a pilot investigation with 3 specimens per group. According to the anticipated power of 80% and effect size ($d=2.12$), estimating 5 specimens per group, the study groups involved 20 dental crowns ($n=10/\text{group}$).

All-ceramic crown preparation of a typodont mandibular first molar tooth was performed,¹⁷ followed by making molds from an additive silicone (President; Coltène whaledent, Altstätten, Switzerland) to produce 20 epoxy resin model duplications.^{18,19} According to this design, PEEK discs (breCAM.BioHPP Discs, bredent, Senden, Germany) were used to mill 20 substructures (K5; vhf camfacture AG, Germany) from.¹⁸ All substructures were blasted with 110 μm aluminum oxide (Al_2O_3) particles (basic Quattro IS; Renfert, Hilzingen, Germany) and then ultrasonically cleaned for 5 min

(L&R Transistor Ultrasonic T14, L&R, Kearny, NY).¹⁸ Later, the PEEK substructures were prepared by a thin layer of primer (visio.link; bredent, Senden, Germany) and light-cured immediately for 90 sec (Brelux Power Unit, intensity: 220 mW/cm₂; bredent, Senden, Germany). Subsequently, an opaquer composite (combo.lign opaquer; bredent, Senden, Germany) was thinly layered and cured for 360 sec.

Ten PEEK substructures were digitally veneered with CAD/CAM micro-filled composite (HIPC; bredent, Senden, Germany). Two scans for the master crown waxing up were attained; one for the model with PEEK substructure on and another for the model with the master crown on. The digital veneer design was created by subtracting both scans, later breCAM.HIPC discs were used to produce the milled design. The resulting veneer's inner surface was blasted, subjected to 5 min ultrasonic cleaning, and then dried. Then, visio.link was used to condition the veneer and cured as described above. A luting composite (combo.lign; bredent, Senden, Germany) was applied to each veneer before being pressed and bonded to its substructure. After 180 sec of curing, the excess luting composite was removed. Finally, finishing and polishing were carried out (Opal L; Renfert GmbH, Hilzingen, Germany; Abraso Starglanz; bredent, Senden, Germany).

Other 10 PEEK substructures were conventionally veneered with nanohybrid composite (Crea.lign; Visio.lign veneering system, bredent, Senden, Germany). A translucent silicone mold (visio.sil; bredent, Senden, Germany) for the master crown was fabricated. Firstly, the mold was filled with Crea.lign composite resin. Then, the epoxy resin model with the attached PEEK substructure was pressed into the silicone mold. Finishing and polishing were performed as previously clarified.

Following the manufacturer's directions, all crowns were bonded with their epoxy resin models utilizing self-adhesive resin cement (RelyXTM Unicem 2; 3M ESPE, Seefeld, Germany).^{18,20,21} For

5 min all crowns were subjected to 250 g static load to ensure proper cement flow and crown adaptation.

A dual-axis chewing simulation machine (four-station multimodal ROBOTA chewing simulator; ROBOTA Co., Giza, Cairo, Egypt) with a thermocyclic system on servomotor (model ach-09075dc-t; AdTech technology Co., Shenzhen, China) was used to evaluate the two-body wear. All specimens were antagonized using 6 mm diameter steatite balls (Höchst CeramTec; Wunsiedel, Germany), where a new steatite antagonist was used for each specimen.²² Both groups' specimens were evaluated consecutively for 120,000 cycles to simulate 6 months of clinical service under 5 kg weight, equal to 49 N chewing force.²³ The loading was applied through a three-step movement: A 1 mm at 40 mm/s descending movement till attaining a contact between the steatite ball and buccal cusp was applied to transfer the total load to the crown, followed by 3 mm at 40 mm/s horizontal movement toward the occlusal sulcus that was ended by direct returning of the steatite ball to its original position. The specimens were then subjected to 3 min ultrasonic cleaning in distilled water.

Following the consistent methodology, scanning the dental crowns' surfaces was performed before and after wear testing. All inspected specimens were profiled by applying a scan powder (Renfert Scanspray; Renfert GmbH Co., Hilzingen, Germany).²⁴ Using a triangulation measurement technology, a 3D dental scanner (Identica Hybrid T500; MEDIT corp., Seoul, Korea) with Mono 2.0 MP resolution and <7 µm accuracy to attain the 3D Standard Tessellation Language (STL) models was used. A software (Geomagic Design X; 3D Systems, Seoul, Korea) was used to import and analyze the digitalized 3D models. From 3D scan data, the optimum 3D mesh models (Fig. 1A) were obtained and converted into CAD surface parts (Fig. 1B).

Before/reference (CAD reference model-CRM) and after/measured (CAD test model-CTM) data

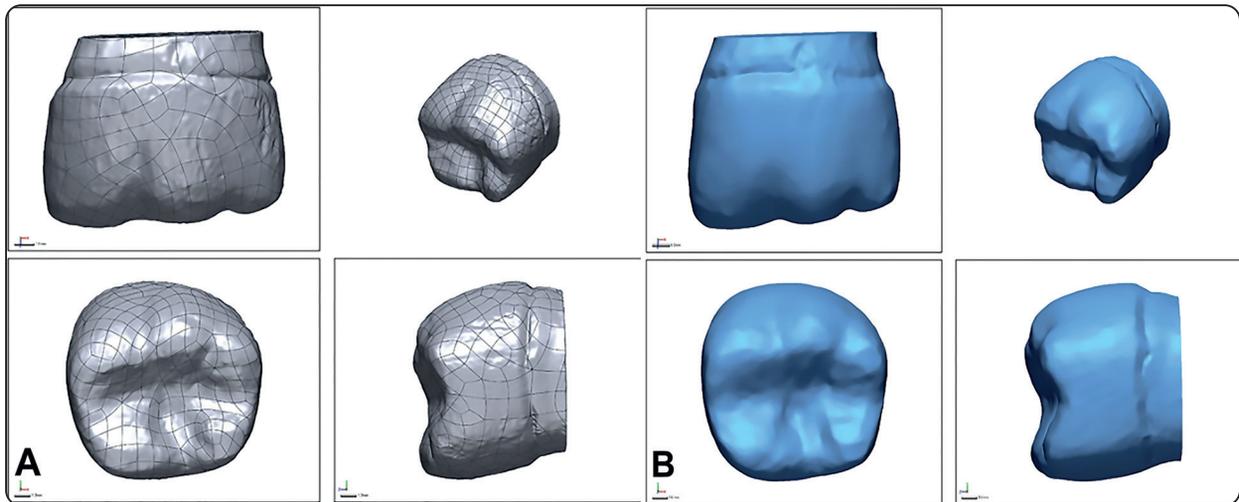


Fig. (1) CRM (A) and CTM (B) of a composite veneered CAD/CAM PEEK crown specimen before and after wear simulation, respectively.

points were superimposed to identify geometric dimensional deviations and wear measurements (Fig 2). The x-, y-, and z-coordinates were inspected. The Enhanced Alignment Accuracy with Feature Recognition feature was utilized to establish an initial alignment between both datasets. This step aimed to ensure standard 3D references' matching and computerized fitting. For the 2D comparison, 6 cross-sections analysis was performed with set 5 mm tolerance values allowing numerical values procurement to establish the average and highest depth values and determine the volume loss (mm^3) (Fig 3).

The calculated deviation values from zero between two sets were displayed as root mean square (RMS) values where all data-point clouds were used in the following equation.²⁵⁻²⁷

$$RMS = \frac{1}{\sqrt{n}} \times \sqrt{\sum_{i=1}^n (X_{1,i} - X_{2,i})^2}$$

Where $X_{1,i}$ is the CRM data point of i , $X_{2,i}$ is that of CTM, and n is the number of all measured points in each analysis.

A distinct color map with a 100 μm range (20

color segments) and $\pm 5 \mu\text{m}$ tolerance range (green) indicating no change were used (Fig 2). More precisely, the red area indicating positive deviation (5 m to 100 m) demonstrated that the CTM data was greater than the CRM data, showing areas of increase. The negative variances ($-5 \mu\text{m}$ to $-100 \mu\text{m}$) in the blue area revealed that the CTM data were lower than the CRM data, suggesting areas of loss. On the other hand, the green area ($\pm 5 \mu\text{m}$) accurately identified the scanned locations indicating excellent 3D superimposition. The horizontal displacement was also estimated as the RMS in the theoretical plane.

Statistical analysis

The normality of quantitative data was investigated by checking data distribution. The non-parametric distribution of data was shown using the Kolmogorov-Smirnov and Shapiro-Wilk tests. The Mann-Whitney U test was used to compare the two groups' median, range, mean, and SD values. The significance level was set at $P \leq 0.05$. Statistical analysis was conducted with statistics software (IBM SPSS Statistics for Windows: Version 23.0; IBM Corp., Armonk, NY).

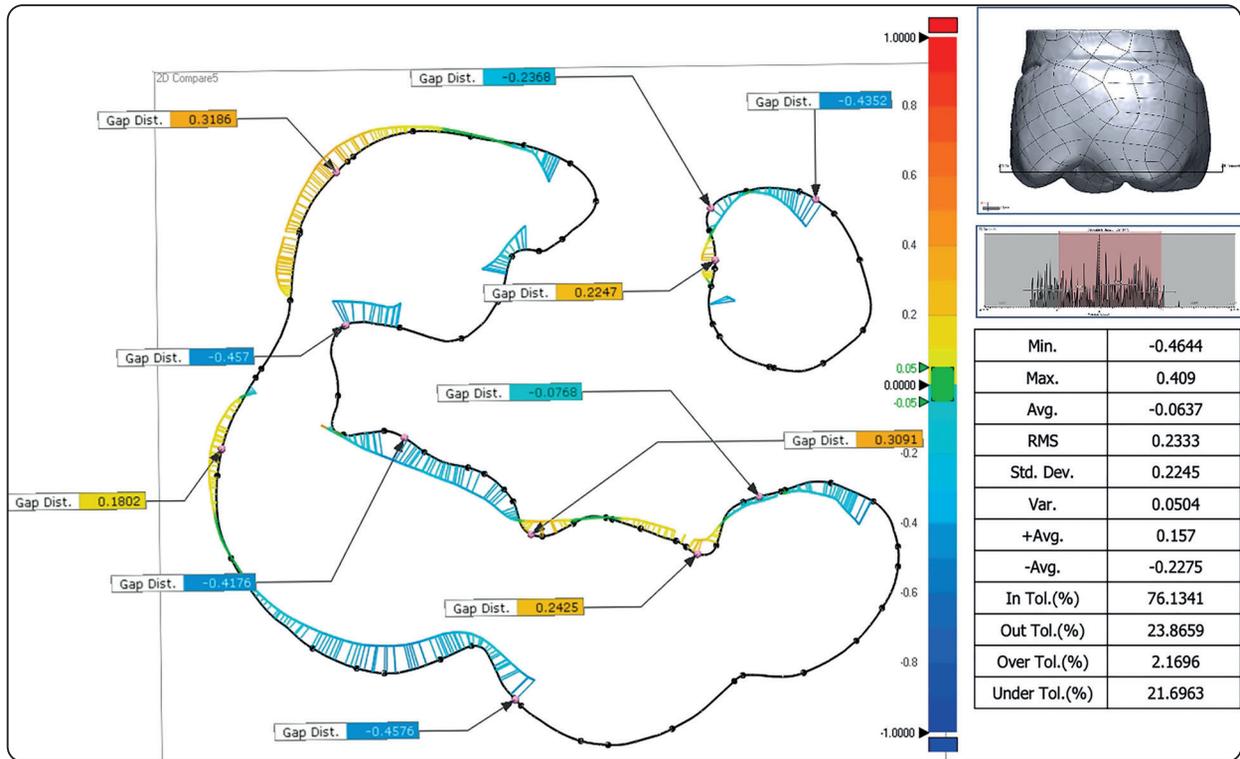
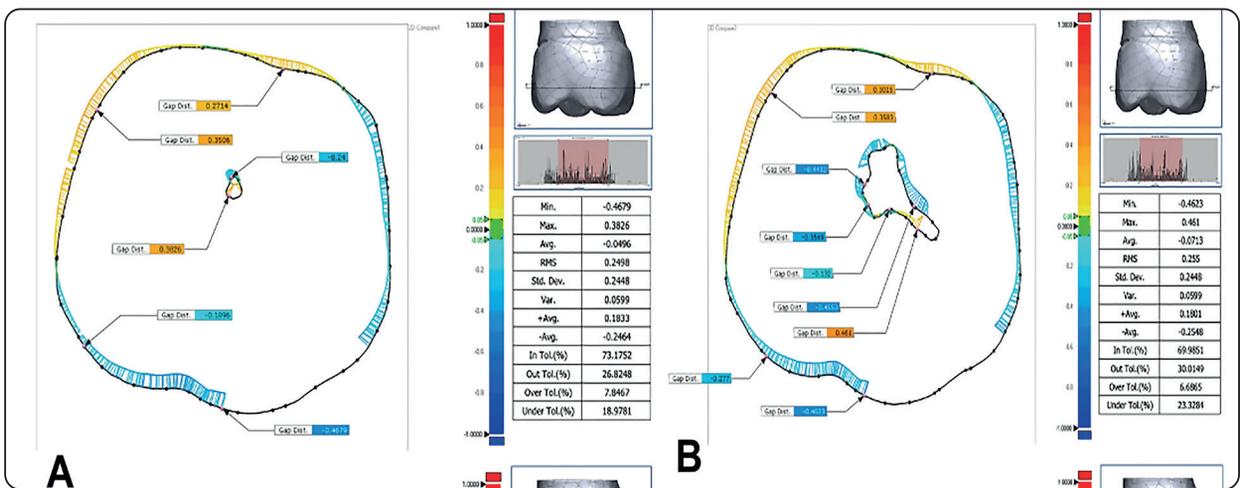


Fig. 2. A cross-section for a tested specimen using a color difference map showing the 2D geometric dimensional deviation comparison between reference & measured (black dots) data. The site of the cross-section of tested crown is presented in the upper right corner.



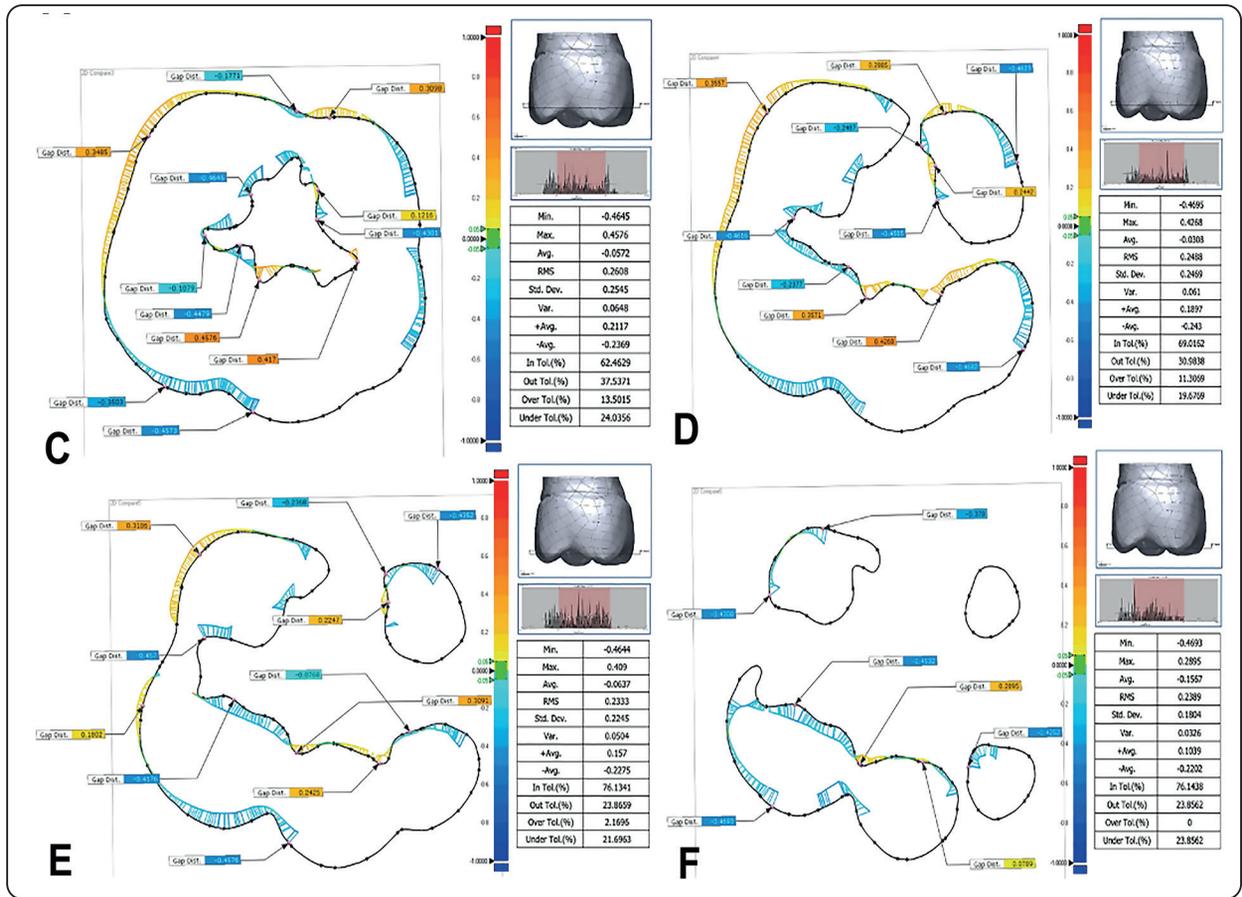


Fig. (3) Six cross-sections (A, B, C, D, E, and F) showing 2D comparison analysis for superimposed reference and measured datasets of composite veneered CAD/CAM PEEK crown.

RESULTS

HIPC group revealed decreased measuring values in comparison to the reference position, while Crea.lign group showed increased measurement. However, HIPC group (-0.0398 [-0.0913- -0.0042] mm³) showed statistically significant lower median volumetric wear loss than Crea.lign group (0.1195 [0.0233- 0.233] mm³) (P-value = 0.050, Effect size = 2.928) (Table 1).

Table (1): Descriptive statistics of Mann-Whitney U test for comparison between wear measured by 3D deviation in the two groups.

HIPC (n = 10)		Crea.lign (n = 10)		P-value	Effect size (d)
Median (Range)	Mean (SD)	Median (Range)	Mean (SD)		
-0.0398 (-0.0913- -0.0042)	-0.0452 (0.0436)	0.1195 (0.0233-0.233)	0.1253 (0.105)	0.050*	2.928

*: Significant at P ≤ 0.05.

DISCUSSION

Monolithic PEEK restoration is limited due to its low translucency and white-opaque color. As a result, additional composite resin veneering is required to achieve acceptable aesthetics.^{12,28} Cera-lign and HIPC veneering composite materials revealed valuable mechanical properties, so they were chosen as test materials.^{15,29} The hypothesis that HIPC veneered PEEK crown would show more wear resistance was confirmed.

In this study, anatomical-shaped crowns were chosen. This geometry was assumed to provide more lifelike conditions in the mouth regarding tooth/dental material wear during function. On the other hand, experimenting with reduced occlusal morphology showed a simplified wear analysis but a low correspondence between laboratory and clinical circumstances.^{1,2,30-32}

Using human enamel cusps as antagonistic abraders might be weak for standardization.³³ Thus, steatite balls were used as they have shown proper antagonists in literature.³⁴⁻³⁶ To overcome inaccurate mimicking of steatite balls to the complex enamel structure, the closest hardness property to enamel was selected (steatite: 680 HV enamel: 330 HV).^{34,37}

The wear loss has been assessed using a variety of qualitative and quantitative methodologies. The qualitative loss evaluation was conventionally measured by indices that exhibited unsatisfactory results.^{1,38} For this reason, quantitative techniques on 3D dental models have been developed.³⁹ Virtual object reconstruction using 3D scanners permits analyzing its dimensions and surface.^{40,41} Accuracy is fundamental for any scanner, which involves exactness-deviation of the scanned object from its actual geometry and precision-deviation between repetitive scans.^{4,42,43} In this investigation, a high-accuracy 3D scanner (<7 μm) was used to limit the impact of the scanner's inaccuracy on results. Its precision is comparable to or better than other techniques like profilometry.¹ To evaluate the

scanner's ability to detect minor alterations in the scanned surface, 120,000 loading cycles (equal to 6 months) were chosen.³¹ On the other hand, it was reported that new tactile probes outperformed 3D scanners in terms of accuracy, which could be advantageous during the dental materials evaluation of wear.⁴⁰

Vertical height loss and 2D outcomes for tooth/dental material wear assessment were more clinically relevant since tooth size had no effect.^{1,44} However, volumetric measurements were more clinically related and provided more information.^{1,45} The earlier wear appraisal methods have been informed that whole accuracy differs vertically from 15 to 30 μm based on the variations in teeth, patients, and researches.¹ In the present research, the utilized assessment method showed a higher accuracy to former techniques as the -0.0398 mm^3 wear volume would be almost 12 μm vertical loss.

The matching software can be added a crucial influence on tooth wear outcomes. The used software could be comparable to extensively tested previous softwares for models' superimposition and processing and verified to perform satisfactorily.^{1,28,46-48} Likewise, the current technique presented visual appraisal through calculation based on thousands of 2D measurements and color-coded distance maps on the entire changed surface available to the operator. As a superimposition reference area, the entire crown was chosen to obtain similar results to the actual values.⁴⁵ As the entire occlusal surface was utilized to assess wear loss, it is proper to measure elected surfaces by isolating the attention volume via slicing. So, the operator's influence on the results was diminished where the selection of reference site was direct and the matching procedure was automated.

As deviatoric mechanisms in composite resin happened, the following equation ($V_{\text{CAV/DEV}} = V_{\text{S}} - V_{\text{S DIL}}$) representing the difference between the measured (V_{S}) and predicted ($V_{\text{S DIL}}$) volume strains

would contribute negatively to the predicted volume strain as shear banding took place.⁴⁹ Nevertheless, positive results demonstrated increased material volume, illustrating the impact of the deformation of polymeric materials on superimposition. This could be explained by the lateral contraction ratio, which determines the dilational response in the material bulk under stress generated by hydrostatic tension.⁴⁹

Different volumetric wear loss for composite resins has been published. Flat specimens, 120,000 chewing cycles, and lateral movement resulted in $5.5\text{-}147 \times 10^{-2}$ mm³ volumetric wear loss as reported by Heintze et al.⁵⁰ Under the same in vitro conditions, Lazaridou et al. found $104.6\text{-}373.8 \times 10^{-3}$ mean volume loss for examined composite materials.⁵¹ While Wimmer et al.'s findings showed the mean volume loss of investigated CAD/CAM nanohybrid composite crowns with and without lateral movement was 118×10^6 μm³ and 19.59×10^6 μm³, respectively.³¹ The mean volume loss for HIPC and Crea.lign in the current study was -39.8×10^{-3} and 119.5×10^{-3} mm³, respectively. However, because the material indication and method were different, the wear rate of the tested composite resins could not be compared to prior findings.^{1,30,32,52} Despite the cyclic contraction/expansion stresses and mechanical load, no veneering composite cracking or separation from substructures was observed. Clinical wear investigations are still required since behavior patterns can change intraorally.

HIPC showed a significant lower wear volume loss (-0.0398 [-0.0913 - -0.0042] mm³) compared to Crea.lign (0.1195 [0.0233 - 0.233] mm³). High pressure and temperature polymerization (250 bar pressure at 120°C) may account for the lower volume loss of CAD/CAM composite resins. Both improved the physical property by converting up to 99.9% of methyl methacrylate to PMMA. This process improves matrix abrasion resistance, hardness characteristics, or two-body wear of composite resins as more chemical bonds are created and fewer free double bonds are found, which may

cause degenerative processes.⁵³ Lauvahutanon et al. confirmed these results and reported that the CAD/CAM composite resins exhibited low wear compared to direct composite resin restorations using similar wear tests.⁵⁴ However, tensions can develop inside the composite structure during the polymerization process, leading to water absorption and cracking that negatively affect the material's properties.^{55,56}

Micro-ceramic particles in HIPC might play a significant role in protecting its surface from wear during the friction force application and developing the HIPC's higher fracture toughness.⁵⁷ However, it is claimed that the existence of large particles as micro-ceramics could theoretically lead to further erosion of the restorative material in wear tests.⁵⁸ When the restoration is subjected to chewing forces, the stress extends through resin-filler particles to the resin matrix resulting in easy elimination of these particles from the surface, exposing the organic matrix, and accelerating wear.⁵¹ Furthermore, some micro-filled composites exhibit comparatively low abrasion and fatigue wear because their relatively low elastic modulus contributes to low contact stresses and lower wear loss.⁵⁸⁻⁶¹

Crea.lign composite had a higher volumetric wear loss than HIPC. This could be due to a high filler content exceeding the threshold levels, reducing abrasion resistance.⁶² In addition, another study found a link between hardness and abrasion behavior, revealing that the volume loss of the investigated material is proportional to the hardness levels.⁶³ One explanation could be that the SiO₂ fillers' porosity which assures matrix penetration and a strong filler-matrix bond, leads to less soluble fillers behaving as abrasive particles.⁶⁴ However, nanocomposites (nanohybrid or nano-filled composites) were reported to have lower abrasion than microhybrid or hybrid composite resins.^{65,66}

The chief limitation of this study was that the advocated approach did not analyze the genuine patient data to validate the accuracy of wear results.

Furthermore, the current wear investigation method used just one type of extraoral scanner. The inability of optical 3D acquisition technologies to scan the highly reflective surfaces of a dental crown should be considered. As a result, powder-free scanning methods should be examined to see if they can produce similar findings.

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