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Comparative Evaluation of Enamel Wear Opposing Monolithic Zirconia, Glass Ceramic and Metal: An Invitro Study

An in Vitro Assessment of Wear Depth and Surface Roughness of Human Enamel

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Abstract:

- ***Background:***

The wear of opposing enamel is an important consideration when selecting restorative materials, particularly for posterior restorations. Material composition and surface characteristics may influence the extent of antagonist enamel wear. This study compared the wear behaviour of enamel opposing metal, glass ceramic, and monolithic zirconia.

- ***Aim:***

To comparatively evaluate maximum wear depth (Dmax), mean wear depth (Da), and average surface roughness (Ra) of human enamel following standardized abrasion against metal, glass ceramic, and monolithic zirconia.

- ***Materials and Methods:***

Thirty extracted, unrestored, non-carious human permanent molars were divided into three groups of 10 specimens each according to the antagonist material: metal, glass ceramic, and zirconia. Wear testing was performed using a pin-on-disc abrasion tester at a load of 25 N and 20 cycles/min. Enamel surface characteristics were quantitatively evaluated using optical profilometry, while scanning electron microscopy was used for qualitative assessment. One-way ANOVA was used for statistical analysis.

- ***Results:***

Significant differences were observed among the three groups ($p < 0.001$). Glass ceramic demonstrated the highest Dmax (2.64 ± 0.16), Da (2.45 ± 0.14), and Ra (3.43 ± 0.10). Metal demonstrated the lowest values, with Dmax of 0.62 ± 0.12, Da of 0.46 ± 0.24, and Ra of 0.43 ± 0.10. Zirconia exhibited intermediate values.

- ***Conclusion:***

Within the limitations of this in vitro study, glass ceramic produced the greatest enamel wear, whereas metal produced the least. Monolithic zirconia demonstrated intermediate wear behaviour.

Keywords: *Dental Ceramics; Enamel Wear; Glass Ceramic; Metal; Monolithic Zirconia; Surface Roughness; Wear Depth.*

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I. INTRODUCTION

Wear of dental hard tissues is a physiological and multifactorial phenomenon that occurs as a consequence of repeated contact and relative movement between opposing surfaces.[1] In the oral environment, wear may occur through tooth-to-tooth or tooth-to-restoration contact and is influenced by several factors, including occlusal relationships, dietary abrasiveness, tooth brushing, parafunctional activity, and the characteristics of the restorative material.[2,3] The introduction of restorative materials into the oral cavity may consequently alter established patterns of occlusal interaction and may contribute to abnormal wear of the opposing dentition.[4]

The increasing demand for tooth-coloured posterior restorations has expanded the use of ceramic materials in contemporary restorative dentistry. Dental ceramics offer favourable esthetics, biocompatibility, chemical stability, and the ability to achieve highly polished surfaces, making them suitable for both anterior and posterior restorations.[5,6] However, the interaction between ceramic restorations and opposing enamel remains an important clinical consideration. Enamel wear associated with ceramic restorations is influenced not only by material hardness but also by surface roughness, fracture toughness, surface condition, and the microstructural characteristics of the ceramic.[7-9] Studies have demonstrated that glazed, polished, and roughened ceramic surfaces can exhibit substantially different effects on the opposing enamel, highlighting the importance of appropriate surface finishing and maintenance.[10,11]

An ideal restorative material should reproduce the function of the natural tooth while maintaining an acceptable rate of wear of both the restoration and its antagonist. Ideally, the wear characteristics of an esthetic restoration should approximate those of the enamel it replaces without accelerating wear of the opposing tooth structure.[9] The development of high-strength ceramic systems has therefore focused on achieving an appropriate balance between mechanical performance, esthetics, and biological compatibility.[11]

Monolithic zirconia has emerged as an important restorative material, particularly for posterior applications. Its high fracture resistance, ability to withstand functional forces in relatively thin sections, and elimination of the veneering porcelain layer have contributed to its increasing clinical use.[12] The transformation-toughening mechanism of zirconia contributes to its resistance to crack propagation and provides greater fracture strength compared with conventional dental porcelains.[13] Nevertheless, the effect of zirconia on opposing enamel remains clinically relevant, particularly because surface characteristics may change following adjustment, polishing, or functional wear.[14,15]

Previous investigations have evaluated enamel wear against various restorative materials, including gold, porcelain, glass ceramics, and zirconia, with considerable variation in experimental design and reported outcomes.[16-18] Although several studies have addressed ceramic-induced enamel wear, direct comparative evaluation of enamel abrasion against monolithic zirconia, glass ceramic, and metal under standardized in-vitro conditions remains relevant.[16-19] The present study was therefore undertaken to comparatively evaluate the maximum wear depth, mean wear depth, and average surface roughness of enamel following abrasion against metal, glass ceramic, and monolithic zirconia using a standardized pin-on-disc wear testing protocol. The findings may contribute to a better understanding of the tribological behaviour of these restorative materials and assist in informed material selection and surface management in prosthodontic practice.

Thus the aim of the present in vitro study aimed to comparatively evaluate the wear of human enamel opposing metal, glass ceramic, and monolithic zirconia, with specific assessment of the maximum wear depth (Dmax), mean wear depth (Da), and average surface roughness (Ra) following standardized abrasion testing.

II. MATERIALS AND METHODOLOGY

➢ *Study Design*

The present investigation was conducted as an in vitro comparative study to evaluate the wear behaviour of human enamel when opposed by three different restorative materials: metal, glass ceramic, and monolithic zirconia. The study was designed to compare the extent of enamel wear produced by these materials under standardized abrasion conditions. The primary parameters evaluated were maximum wear depth (Dmax), mean wear depth (Da), and average surface roughness (Ra). The experimental protocol was based on a pin-on-disc wear abrasion system followed by quantitative evaluation using an optical profilometer and qualitative assessment using scanning electron microscopy (SEM).

➢ *Materials and Armamentarium*

Thirty extracted human permanent molars were used for preparation of enamel test specimens. The teeth were selected to be unrestored, non-carious, non-hypoplastic, and clinically sound. Medium-grit carborundum discs, a laboratory micromotor, and autopolymerizing polymethyl methacrylate (PMMA) resin were used for preparation and embedding of the enamel specimens.

For fabrication of the metal specimens, inlay casting wax and a nickel-chromium alloy were used. Pressable lithium disilicate glass ceramic specimens were fabricated using IPS e.max esthetic ceramic ingots and an Ivoclar Vivadent EP3000 Combi Press furnace. Zirconia specimens were fabricated using a master die and a CAD/CAM milling and sintering system. A pin-on-disc abrasion tester was used for the wear experiment.

➢ *Preparation and Grouping of Enamel Specimens*

Thirty extracted, unrestored, non-carious, non-hypoplastic, sound human permanent molars were selected. The extracted teeth were cleaned using an ultrasonic scaler and subsequently stored in deionized water. The occlusal surfaces were reduced using a rotary cutting instrument under

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water cooling to obtain enamel specimens suitable for the wear test.

The specimens were divided into three experimental groups, with 10 specimens in each group:

- Group A: Human enamel specimens abraded against metal.
- Group B: Human enamel specimens abraded against glass ceramic.
- Group C: Human enamel specimens abraded against zirconia.

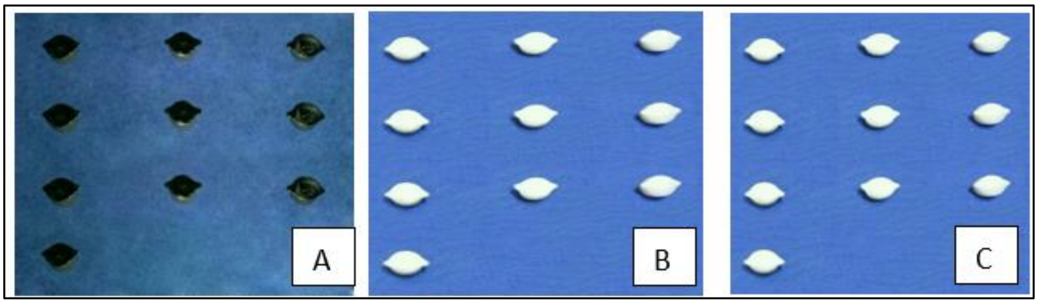

Fig 1. A. Metal Specimens B. Glass Ceramic Specimens C. Zirconia Specimens

Thus, a total of 30 enamel specimens were included in the study.

➢ *Fabrication of Master Die*

An impression of the mould space was made using an addition silicone elastomeric impression material. The resulting impression was used to fabricate a master die. Inlay casting wax was adapted over the die to produce standardized wax patterns. The wax patterns were subsequently invested and cast using nickel-chromium alloy. The castings were finished and polished and subsequently used as the master die for fabrication of the test specimens.

➢ *Fabrication of Metal Specimens*

Thirty wax patterns were fabricated using the master die. The patterns were subsequently invested and cast using nickel-chromium alloy. The resulting metal specimens were finished and prepared as discs measuring approximately 10 mm × 5 mm.

➢ *Fabrication of Glass Ceramic Specimens*

Thirty standardized wax patterns were prepared using the master die and subsequently invested using refractory investment material. Pressable lithium disilicate ceramic ingots (IPS e.max esthetic ceramic) were melted and pressed into the prepared moulds using the manufacturer-recommended furnace. The resulting specimens were fabricated as discs measuring approximately 10 mm × 5 mm.

➢ *Fabrication of Zirconia Specimens*

The master die was scanned, and the digital information was used for fabrication of zirconia specimens using a CAD/CAM system. The zirconia discs were subsequently milled and sintered to obtain the required test specimens.

➢ *Mounting of Enamel Specimens*

The prepared enamel specimens were centrally embedded in autopolymerizing PMMA resin. The embedded specimens were placed into the upper specimen holder of the abrasion apparatus. A screw mechanism within the holder permitted vertical adjustment and stabilization of the specimen. The upper holder was connected to the lever arm of the device. The corresponding antagonist specimen was placed in the lower specimen holder, which was capable of rotational movement in a clockwise direction.

➢ *Baseline Surface Roughness Measurement*

Prior to abrasion testing, baseline measurements of the enamel surfaces were obtained using an optical profilometer. The mean surface roughness was recorded from unworn portions of the enamel specimens. These baseline measurements provided a reference for subsequent evaluation of changes in enamel surface characteristics following the wear experiment.

➢ *Abrasion Testing Procedure*

Wear testing was performed using a pin-on-disc wear abrasion tester. The rate of cycling and duration of the experiment were controlled using the device control system and monitored using a digital counter. The enamel specimens were subjected to a standardized load of 25 N at a cycling rate of 20 cycles per minute. The enamel specimens were abraded against the three experimental antagonist materials like metal, glass ceramic, and zirconia.

Following completio of the abrasion test, the enamel specimens were examined quantitatively using an optical profilometer. The parameters recorded were average surface roughness (Ra), mean wear depth (Da), and maximum wear depth (Dmax). These measurements were used to compare the extent of enamel surface alteration produced by the three restorative materials.

➢ *Scanning Electron Microscopic Evaluation*

For qualitative characterization of the wear patterns, the enamel specimens were examined using scanning electron microscopy. The surfaces were evaluated at 300× magnification and 15 kV following the abrasion procedure. SEM examination was performed to characterize the morphological features associated with the wear produced on the enamel surfaces.

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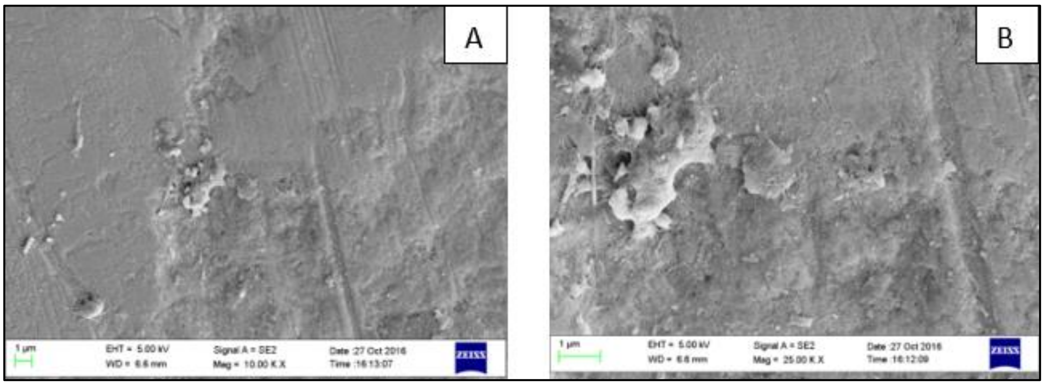

Fig 2. Scanning Electron Micrograph of Surfaces of Test Specimens at Baseline and after 4800 Cycles of Wear Testing for Metal Specimens (A) Before (B) After

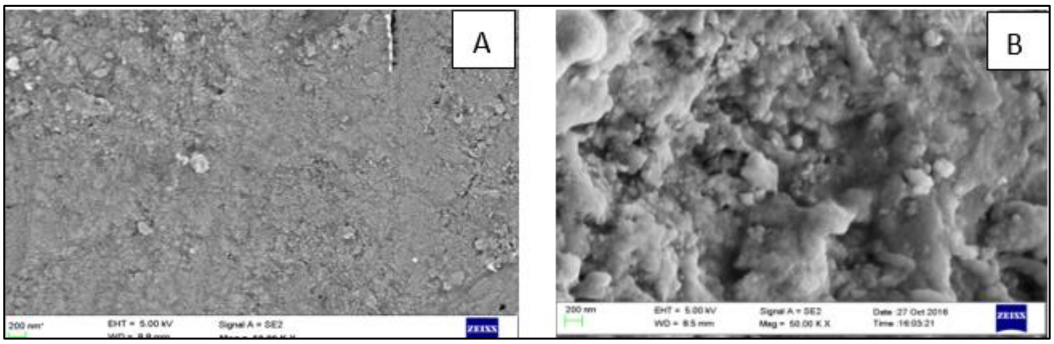

Fig 3. Scanning Electron Micrograph of Surfaces of Test Specimens at Baseline and after 4800 Cycles of Wear Testing for Glass Ceramic Specimens (A) Before (B) After

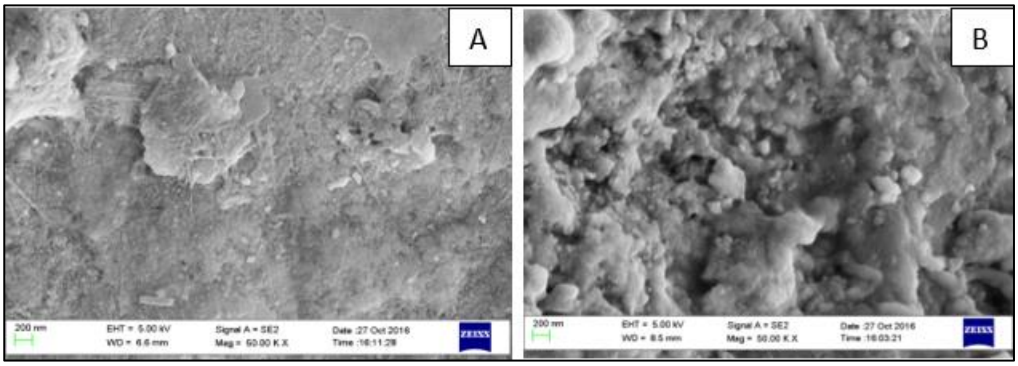

Fig 4. Scanning Electron Micrograph of Surfaces of Test Specimens at Baseline and after 4800 Cycles of Wear Testing for Zirconia Specimens (A) Before (B) After

➢ *Statistical Analysis*

The recorded measurements of maximum wear depth, mean wear depth, and average surface roughness were subjected to statistical analysis. One-way analysis of variance (ANOVA) was used to compare the groups. The study demonstrated statistically significant differences in maximum wear depth, mean wear depth, and average surface roughness among the tested materials, with $p < 0.001$ reported for the comparisons described in the results. The experimental methodology therefore enabled standardized quantitative comparison of enamel wear against metal, glass ceramic, and zirconia, while profilometric and SEM evaluations provided complementary quantitative and qualitative assessment of the resulting surface changes.

III. RESULTS

The present in vitro study evaluated the wear characteristics of human enamel following abrasion against three different restorative materials: metal, glass ceramic, and zirconia. A total of 30 enamel specimens were evaluated and divided into three groups of 10 specimens each. Group A consisted of enamel specimens abraded against metal, Group B consisted of enamel specimens abraded against glass ceramic, and Group C consisted of enamel specimens abraded against zirconia.

Following the abrasion procedure, the enamel specimens were evaluated using an optical profilometer. The profilometer used a 1300-nm infrared laser to scan the surface of the specimens and record the average surface roughness (Ra). The measurements were obtained according to ISO

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4287 recommendations. One-way analysis of variance (ANOVA) was used for statistical analysis.

➢ *Maximum Wear Depth*

The maximum wear depth (Dmax) demonstrated considerable variation among the three experimental groups. The enamel specimens abraded against metal showed the lowest mean maximum wear depth, measuring 0.62 ± 0.12. In comparison, the mean maximum wear depth increased to 1.64 ± 0.16 for zirconia and was highest for glass ceramic, measuring 2.64 ± 0.16.

A statistically significant difference was observed between the groups. The difference in maximum wear depth between enamel abraded against glass ceramic and zirconia was statistically significant, with the overall comparison demonstrating a highly significant difference ($p < 0.001$).

Table 1. Distribution of Maximum Wear Depth (Dmax) of Enamel

Antagonist Material	**Maximum Wear Depth (Mean ± SD)**
Metal	0.62 ± 0.12
Glass ceramic	2.64 ± 0.16
Zirconia	1.64 ± 0.16
P value	**<0.001**

➢ *Mean Wear Depth*

The mean wear depth (Da) showed a pattern similar to that observed for maximum wear depth. The lowest mean wear depth was recorded in enamel specimens abraded against metal, with a value of 0.46 ± 0.24. Enamel specimens abraded against zirconia demonstrated an intermediate mean wear depth of 1.45 ± 0.14, whereas the highest mean wear depth was recorded against glass ceramic, measuring 2.45 ± 0.14.

The difference in mean wear depth between the experimental groups was statistically significant. The study reported a highly significant difference following abrasion, with $p < 0.001$.

Table 2. Distribution of mean wear depth (Da) of enamel

Antagonist Material	**Mean Wear Depth (Mean ± SD)**
Metal	0.46 ± 0.24
Glass ceramic	2.45 ± 0.14
Zirconia	1.45 ± 0.14
P value	**<0.001**

➢ *Average Surface Roughness*

The average surface roughness (Ra) of enamel was also assessed following the abrasion test. The lowest mean surface roughness was observed in enamel specimens abraded against metal, with a value of **0**.43 ± 0.10. Enamel specimens abraded against zirconia demonstrated an intermediate value of 1.43 ± 0.10, while the highest average surface roughness was recorded in specimens abraded against glass ceramic, measuring 3.43 ± 0.10.

The difference in average surface roughness among the experimental groups was statistically significant, with $p < 0.001$. Thus, the enamel specimens opposing glass ceramic demonstrated the greatest alteration in surface roughness, whereas those opposing metal demonstrated the least.

Table 3. Comparison of Average Surface Roughness (Ra) of Enamel

Antagonist Material	**Average Surface Roughness (Mean ± SD)**
Metal	0.43 ± 0.10
Glass ceramic	3.43 ± 0.10
Zirconia	1.43 ± 0.10
P value	**<0.001**

Across all three evaluated parameters, a consistent pattern was observed. Glass ceramic demonstrated the highest values for maximum wear depth, mean wear depth, and average surface roughness. Zirconia demonstrated intermediate values for all three parameters, whereas metal consistently demonstrated the lowest values.

For maximum wear depth, the value recorded against glass ceramic was approximately four times that observed against metal. Similarly, mean wear depth was substantially greater against glass ceramic than against metal. Average surface roughness followed the same pattern, with the highest value recorded following abrasion against glass ceramic.

Table 4. Overall Comparison of Enamel Wear Parameters

Parameter	**Metal**	**Glass ceramic**	**Zirconia**
Maximum wear depth (Dmax)	0.62 ± 0.12	2.64 ± 0.16	1.64 ± 0.16
Mean wear depth (Da)	0.46 ± 0.24	2.45 ± 0.14	1.45 ± 0.14
Average surface roughness (Ra)	0.43 ± 0.10	3.43 ± 0.10	1.43 ± 0.10

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Overall, the findings demonstrated statistically significant differences in enamel wear characteristics among the three antagonist materials, with glass ceramic producing the highest recorded values for all evaluated parameters and metal producing the lowest values. Zirconia consistently exhibited intermediate values between the two materials.

IV. DISCUSSION

The present in vitro study evaluated the wear behaviour of human enamel opposing metal, glass ceramic, and zirconia by assessing maximum wear depth (Dmax), mean wear depth (Da), and average surface roughness (Ra). Statistically significant differences were observed among the three antagonist materials. Glass ceramic produced the greatest enamel wear, whereas metal produced the least, with zirconia demonstrating intermediate values. The maximum wear depth was 2.64 ± 0.16 for glass ceramic, 1.64 ± 0.16 for zirconia, and 0.62 ± 0.12 for metal. A similar trend was observed for mean wear depth and surface roughness, with glass ceramic showing the highest values and metal the lowest.

The greater enamel wear associated with glass ceramic may be explained by the susceptibility of ceramic surfaces to microfracture and the subsequent development of surface irregularities. Ceramic-induced enamel wear is influenced by surface roughness, fracture toughness, and surface condition rather than hardness alone. During functional contact, microfractures may generate surface asperities that increase abrasive interaction with opposing enamel. Furthermore, detached ceramic particles may act as abrasive media and contribute to a three-body wear mechanism.

The present findings are consistent with earlier investigations demonstrating greater enamel wear against porcelain and ceramic materials compared with metallic materials. Previous studies reported minimal wear with gold, whereas glazed and unglazed porcelain produced greater enamel wear. Kadokawa et al. further demonstrated that enamel wear was significantly lower against smooth porcelain than rough porcelain, emphasizing the importance of surface texture in antagonist wear.[20] Similarly, another in vitro investigation comparing different ceramic substrates found gold and polished ceramics to be among the least abrasive materials, while glazed IPS Empress produced the greatest enamel wear, with a significant correlation between surface roughness and enamel wear.[21]

The intermediate wear observed with zirconia is supported by the study of Habib et al., which directly evaluated human enamel opposing monolithic zirconia, glass ceramic, and other restorative materials.[22] Their study reported that monolithic zirconia produced less enamel wear than glass ceramic, with no significant difference in Dmax and Da between monolithic zirconia and composite resin. This observation closely corresponds with the present findings, in which zirconia demonstrated lower Dmax and Da than glass ceramic. The similarity is particularly relevant because both investigations assessed enamel wear using quantitative wear-depth measurements.

In addition, Lohbauer et al. reported that zirconia produced less opposing enamel wear than lithium disilicate after adjustment and polishing, with enamel wear of 0.33 ± 0.11 mm^3 against polished zirconia compared with 0.36 ± 0.09 mm^3 against polished lithium disilicate.[23] This is in agreement with the present study, in which glass ceramic produced greater enamel wear than zirconia. However, the magnitude of wear should not be compared directly because the studies differed in specimen preparation, loading conditions, number of cycles, surface treatment, and methods of wear measurement. More recently, a one-year clinical study by Woraganjanaboon et al. found no significant difference between antagonist enamel wear produced by monolithic zirconia and lithium disilicate crowns, emphasizing that laboratory findings may not always translate directly to clinical conditions.[24]

The relatively lower enamel wear associated with zirconia may be related to its high fracture resistance and reduced susceptibility to microfracture compared with glass ceramic. The crystalline structure of zirconia may restrict microcrack propagation, allowing the surface to remain comparatively smooth during abrasion. The original study discussion similarly proposed that fewer microfractures and a smoother zirconia surface could account for the lower wear depth of opposing enamel. A systematic review has also reported that antagonist enamel wear against zirconia is generally similar to or greater than natural tooth wear but lower than that associated with metal-ceramic restorations.[25]

The present findings are further supported by studies evaluating the influence of zirconia surface treatment. Previous studies has demonstrated that polished monolithic zirconia produces relatively low antagonist enamel wear, whereas surface adjustment, glazing, or increased roughness may alter its wear behaviour. The importance of polishing is therefore clinically relevant because restoration surfaces may become roughened following occlusal adjustment and subsequent functional wear. Maintaining a smooth occlusal surface may consequently help minimize antagonist enamel wear.

The lowest wear values observed with metal are consistent with earlier comparative studies reporting relatively low abrasiveness of gold and other metallic materials toward opposing enamel. However, the wear mechanism of metal differs from that of brittle ceramic and enamel substrates; therefore, hardness alone cannot be considered a universal predictor of antagonist wear.

- *Strengths*

The major strength of the present study was the standardized comparison of three restorative materials under identical experimental conditions. The use of human enamel provided a clinically relevant substrate, while optical profilometry enabled quantitative evaluation of Dmax, Da, and Ra. The use of a standardized pin-on-disc system allowed direct comparison among the materials, while SEM evaluation provided additional morphological information regarding the wear surfaces.

➢ *Limitations*

The findings should be interpreted within the limitations of the in vitro design. Natural enamel is inherently heterogeneous, and differences in enamel thickness, tooth position, and intrinsic properties may influence wear measurements. In addition, the experimental model cannot fully reproduce the complex oral environment, including saliva, temperature fluctuations, lubrication, dietary factors, and three-body wear. Variations in applied load, velocity, number of cycles, and wear-testing methodology also make direct comparison between different investigations difficult. Therefore, the present findings should be interpreted cautiously, and well-designed long-term clinical studies are required to establish the clinical relevance of the observed differences.

V. CONCLUSION

Within the limitations of this in vitro study, significant differences were observed in the wear behaviour of human enamel opposing metal, glass ceramic, and monolithic zirconia. Glass ceramic demonstrated the highest maximum wear depth, mean wear depth, and average surface roughness, indicating greater enamel surface alteration. Monolithic zirconia exhibited intermediate wear values, while metal demonstrated the lowest values among the tested materials. These findings suggest that the antagonist wear behaviour of restorative materials is influenced by their material characteristics and surface properties. The results support careful consideration of restorative material selection and surface finishing, particularly in occlusal contact areas. However, further long-term clinical studies are required to validate these in vitro findings and establish their clinical relevance.

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