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RESEARCH AND EDUCATION

Comparison of wear behavior of occlusal device materials manufactured by different processes

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ABSTRACT

Statement of problem. Occlusal devices have been used for therapeutic and diagnostic purposes. Although their effectiveness in preventing tooth wear has been reported, research regarding the wear of the occlusal device when opposing different materials is lacking.

Purpose. The purpose of this in vitro study was to measure and compare the volumetric wear of conventionally processed, milled, and 3-dimensionally (3D) printed occlusal device materials when opposed by human enamel, lithium disilicate, and 4 mol% yttria-stabilized zirconia.

Material and methods. Milled polymethyl methacrylate (ProArt CAD Splint; Ivoclar AG), printed resin (Next Dent Ortho Rigid), and conventional heat-polymerized polymethyl methacrylate (Vitacrilic Clear; Fricke International, Inc) were tested. Fifteen Ø14×2-mm disk-shaped specimens were fabricated from each manufacturing process. Each material group was divided into 3 groups of 5 specimens and tested against each of the 3 antagonist materials, human enamel, zirconia (IPS e.max ZirCAD MT; Ivoclar AG), and lithium disilicate (IPS e.max CAD; Ivoclar AG) shaped into a spherical stylus. Each specimen was subjected to 50 000 mastication cycles using an oral wear simulator (Oregon Health Sciences University (OHSU) Wear Machine), with a frequency of 1.1 Hz and a maximum 50-N load with vertical load and horizontal movement. The surfaces of the substrate and styli were before and after wear testing using a laboratory scanner (E4 scanner; 3Shape A/S). The surfaces of each specimen before and after wear testing were analyzed using a software program (WearCompare; Leeds Digital Dentistry). The volume difference between the before and after scans were determined for both the substrate and the stylus and analyzed using a 2-way ANOVA. The statistical significance between groups was determined using the Tukey-Kramer HSD test (α=.025).

Results. The results of the 2-way ANOVA showed that the antagonist material ($P<.01$) significantly influenced the resulting volumetric wear of the occlusal device materials, whereas the substrate material ($P=.03$) had no significant effect. The interaction between substrate type and antagonist material ($P=.42$) also did not significantly affect volumetric wear. Only the material type of the opposing antagonist material ($P<.001$) influenced the volume loss, whereas the substrate type ($P=.05$) and interactions ($P=.93$) between these 2 factors were statistically similar.

Conclusions. Significant differences in wear were found among printed, milled, and heat-polymerized polymethyl methacrylate occlusal device materials. The wear of these materials was influenced by both the type of material used and the antagonist materials. The printed occlusal device material exhibited the least amount of wear. (J Prosthet Dent 2026;135:614.e1-e7)

According to the Glossary of Prosthodontic Terms,[1] an occlusal device is "any removable artificial occlusal surface affecting the relationship of the mandible to the maxillae used for diagnosis or therapy." An occlusal device can be used for either therapeutic or diagnostic purposes; for instance, stabilizing the occlusion when

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Clinical Implications

Occlusal devices manufactured from printed materials are a suitable option for patients with parafunctional habits because of their wear resistance.

treating temporomandibular disorders, serving as a diagnostic appliance before extensive rehabilitations, relaxing facial musculature, or preventing the volumetric wear of definitive restorative materials.[1,2]

The introduction of computer-aided design and computer-aided manufacturing (CAD-CAM) has shown promising results in efficiency, speed, and access to materials with good dimensional stability.[3–5] Patzelt et al[6] reported that the digital workflow for fabricating occlusal devices can be more efficient and provide a better fit than traditionally processed polymethyl methacrylate (PMMA). Berli et al[7] reported that conventionally processed occlusal devices and milled resins were comparable in terms of the mechanical properties of the materials. However, 3-dimensionally (3D) printed resins exhibited lower flexural strength, hardness, and degree of conversion, as well as higher water sorption and solubility, compared with milled and pressed PMMA occlusal devices.[7–11]

The mechanical properties of occlusal devices should be assessed, and the clinical relevance of these properties determined for their long-term success.[12] Wear has been reported to impact both the tooth structure and many restorative materials, which must have sufficient mechanical integrity and strength to function effectively in the oral cavity over an extended period.[12]

Many materials and manufacturing processes have been used for the fabrication of occlusal devices.[4] In addition, many materials can oppose the occlusal device, which could affect its wear rate.[13] The mechanical properties, wear behavior, and the effect of these opposing materials, including zirconia, lithium disilicate, and enamel, have been evaluated.[12–17]

Overall, an occlusal device can be in place from several weeks to months depending of the treatment and application.[18] Therefore, occlusal device longevity is a critical factor in treatment success. Although extended clinical trials are not available, medium- to long-term data support the ongoing use of occlusal devices to protect restorations in bruxers.[19–21] Consensus statements further recommend long-term occlusal devices used in at-risk patients.[22,23] Such appliances may not alter bruxism activity but can distribute occlusal load and reduce focal stresses, thereby protecting teeth and restorations from fracture.[22–24] Although the use of occlusal devices to prevent the wear of tooth structure has been well established,[25] research on the potential wear that the opposing teeth and materials may experience during the use of an occlusal device is lacking.[25]

According to the Academy of Dental Materials, intraoral wear occurs through different mechanisms, categorized as either 2-body or 3-body wear.[12] Three-body wear, also known as abrasive wear, involves the presence of a third body, such as toothpaste, food particles, or brushes, between the teeth. In contrast, 2-body wear, also referred to as attrition wear, occurs from direct contact between the teeth without any intervening materials. The International Organization for Standardization (ISO) technical specification on "Guidance on Testing Wear"[13] for in vitro studies describes 8 different test methods for evaluating 2-body and 3-body wear. Although in vitro studies may not fully replicate the oral environment, they provide standardized conditions that enable consistent material comparisons.[26] The Oral Wear Simulator (Oregon Health Sciences University-OHSU) has been reported to correlate with the in vivo wear of composite resin materials, indicating that its results are clinically relevant.[26,27]

The aim of the present in vitro study was to measure the volumetric wear of milled and printed occlusal device materials opposed by different antagonist materials. In addition, the relative volume wear of various antagonist materials was measured. The null hypotheses were that the volumetric wear of the occlusal device material would not be influenced by the materials used or the type of antagonist material and that the wear of the antagonist materials would not be influenced by the occlusal device materials.

MATERIAL AND METHODS

The experimental design included the evaluation of 3 occlusal device materials, a milled polymethyl methacrylate (MMA) (ProArt CAD Splint; Ivoclar AG), a printed resin (PRT) (NextDent Ortho Rigid; Vertex-Dental B.V.), and conventionally processed polymethyl methacrylate (PMA) (Vitacrilic Clear; Fricke International, Inc) and 3 antagonist materials, human enamel (HE), zirconia (ZIR) (IPS e.max ZirCAD MT; Ivoclar AG), and lithium disilicate (LD) (IPS e.max CAD; Ivoclar AG). Based on the error variance of 0.139 mm^3 for the volume loss,[28] a sample size of 3 per subgroup was determined to provide a sensitivity of 0.1 mm^3 at a power of 95%.[29,30] The sample size for the study was increased to 5 to improve sensitivity.

The 3 occlusal device materials were formed into Ø14×2-mm disks by following previously described methodology.[31] The disks were designed digitally with a software program (Meshmixer; Autodesk, Inc) and exported in a standard tessellation language (STL) file. Using a milling machine (R5; vhf camfacture AG), 15

Figure 1. Polished specimens for wear testing. Substrates.

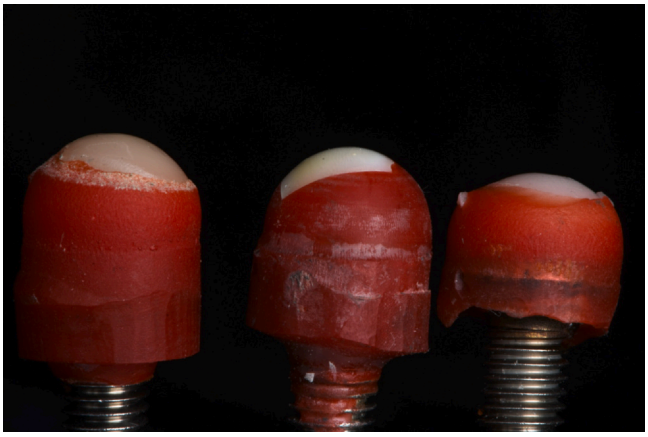

Figure 2. Human enamel tipped. Antagonists. A, HE. B, ZIR. C, LD.

specimens were milled from a PMMA disk (ProArt CAD Splint; Ivoclar AG).[32] Fifteen specimens were printed from resin (Next Dent Ortho Rigid; NextDent, B.V) using a 3D printer (NextDent 5100; 3D Systems Inc).[33] The printed specimens were cleaned with 96% isopropyl alcohol for 10 minutes, air dried for 20 minutes, and postpolymerized in an ultraviolet (UV) lightbox (LC-3DPrint Box; NextDent B.V.), and all supports were removed. The remaining 15 specimens were processed using heat-polymerized PMMA (Vitacrilic Clear; Fricke International, Inc). Printed specimens were flasked in stone with a layer of polyvinyl siloxane (Panasil Putty; Kettenbach Dental Inc) to obtain the same pattern for the conventionally processed PMMA disks. After flask separation and pattern removal, the powder and monomer were mixed and processed according to the manufacturer's instructions.[34] The completed disk specimens were placed face down on a glass slide and embedded in a Ø25-mm hollow acrylic resin ring with autopolymerizing PMMA (Jet Tooth Shade, Jet Liquid; Lang Dental Manufacturing Co, Inc). Subsequently, all specimens were polished using a series of 400-, 1000-, and 2000-grit silicon carbide papers (MicroCut; Buehler Ltd) and water and cleaned for 5 minutes in an ultrasonic bath (OptiSonic; Benco) (Fig. 1).

The antagonists were Ø10-mm spherical tips.[31] For the 2 CAD-CAM materials, a pattern was designed and manufactured digitally using a 3D design software program (Meshmixer; Autodesk Inc). The pattern consisted of a Ø10×10-mm cylinder with a Ø10-mm spherical end. The designed object was exported into an STL file and sent to a milling machine (R5; vhf Inc). Each pill-shaped specimen was sectioned in half, and each half was mounted onto a hexagonal screw head to form the spherical antagonist tips (Fig. 2).

The HE antagonists were extracted human molars teeth, considered medical waste that would be discarded and with no identifiers of any kind. According to Institutional Review Board policies, the use of these specimens does not constitute human subjects research and falls under the exemption category; therefore, they did not require IRB approval. These were sectioned into quarters after the removal of the roots at the level of the cementoenamel junction (CEJ). The enamel and dentin quarters were embedded in a spherical silicone mold and attached to a screw head with the enamel surface exposed.

The embedded teeth were placed in a small machine lathe (Unimat-SL; American Edelstaal Inc) and shaped while rotating with a diamond rotary instrument using a high-speed dental handpiece and water spray mounted to a special 5-mm-radius holder. The resulting specimens are shown in Figure 2. All antagonists were polished using a small lathe (243.6 M; Abrasive Technology LLC) using P1200 and P2000 silicon carbide sheets (MicroCut; Buehler Ltd) and water. Surface scans were made for all specimens and styli using a laboratory scanner (E4 scanner; 3Shape A/S). Coating materials have been recommended for highly reflected surfaces to improve the laser light diffusing and, hence, the scanning process.[35,36] Therefore, spray (Scantist 3D Vanishing Spray; Scantist 3D) was used to improve the scanning process.[37] The Oregon Health Sciences University (OHSU) simulated wear machine[31,38,39] was used to produce sliding contact-type wear on the surface of the specimens (Fig. 3). The device simulated mastication by having the stylus contact the substrate while sliding over the surface for a fixed distance and applying a 50-N load at the end of the stroke. Each specimen was subject to 50 000 mastication cycles, at a frequency of 1.1 Hz. Three milliliters of artificial saliva (Artificial Saliva Medical & Dental; Pickering Laboratories Inc) were introduced into each mastication chamber before testing to more closely simulate the oral condition. After testing, the disk and stylus specimens were rescanned. The surfaces of each specimen before and after wear testing were analyzed using a surface comparing software program (WearCompare; Leeds Digital Dentistry), which allowed areas of no wear to be selected for best-fit

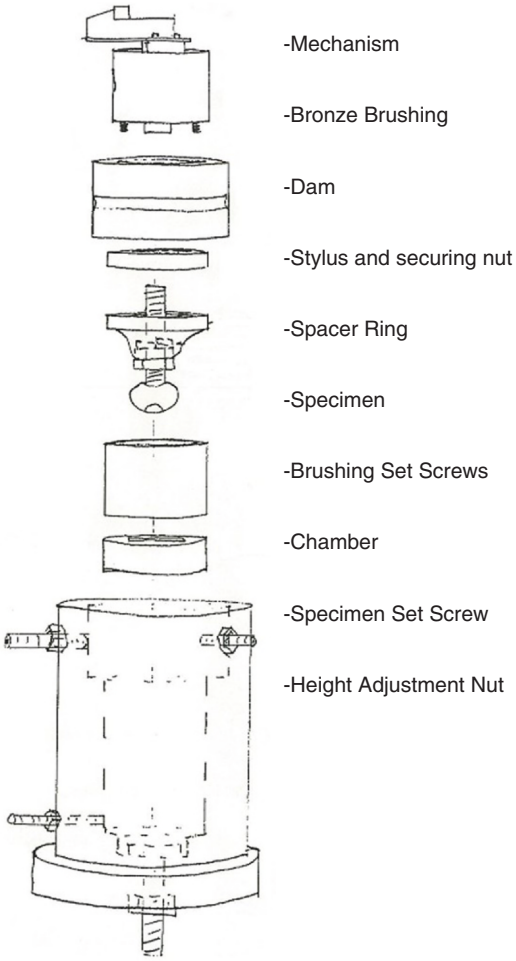

Figure 3. Schematic of Oregon Health Sciences University wear machine.[38,39].

Table 1. Results of two-way Analysis of Variance (ANOVA) of volume loss of substrate material

Source	Number of Parameters	Degree of Freedom	Sum of Squares (mm^3)	F Ratio	*P*
ANT	2	2	10.446	8.544	<.001*
SUB	2	2	4.764	3.897	.029
SUB×ANT	4	4	2.449	1.002	.419

ANT, antagonist; SUB, substrate.

purposes. Its precision and accuracy have been examined and reported to compare favorably with those of similar software programs, including the Geomagic program (Geomagic Control X; 3D system).[40] The volume loss or difference was determined from the before and after scans and reported in cubic millimeters. The data were subjected to a 2-way ANOVA and the Tukey-Kramer HSD post hoc test to determine significant differences between groups (α=.025) with a statistical software program (JMP 17 2022; JMP Statistical Discovery LLC). Since the corresponding antagonist and substrate pairs of each specimen were not kept together for volume loss measurements, a 3-way repeated-measures ANOVA could not be used. Consequently, the allowable Type 1 error was reduced to α=.025 to protect against any Type 1 error in either of the 2 ANOVAs performed.

RESULTS

The results of the 2-way ANOVA concerning substrate wear are presented in Table 1. These results suggest that the antagonist materials (*P*<.001) significantly affected the resulting substrate volume loss, whereas the substrate material (*P*=.029) had no significant effect. The interactions between occlusal device materials and antagonist materials were not statistically significant (*P*>.42). The post hoc Tukey Pairwise Comparison test results on the influence of the antagonist material on the substrate wear (Table 2) showed that the antagonist group of human enamel (HE) had significantly more substrate wear than the lithium disilicate group (LD) (*P*<.01). The group means and standard errors are graphically summarized in Figure 4, which also shows that the group of lithium disilicate with processed polymethyl methacrylate (LD-MMA) differed significantly from the groups of human enamel with print resin (HE-PRT) and zirconia with print resin (ZIR-PRT). In general, the substrate material of print resin (PRT) resulted in the least wear, and the antagonist material of lithium disilicate (LD) had the most volume loss among the antagonists.

Concerning antagonist wear, Table 3 present results of 2-way ANOVA of Volume Loss of Antagonist Materials. It was determined that the material opposing the occlusal device material significantly influenced regarding the amount of antagonist wear (*P*<.001). The type of material device was statistically significant regarding the volume loss of that antagonist wear (*P*<.05). Conversely, the interaction between the antagonist and substrate material was not statistically significant

Table 2. Results of Tukey pairwise comparison tests on influence of antagonist material on substrate wear volume

Antagonist Materials being Compared		Difference (mm^3)	Std Error (mm^3)	t Ratio	*P*	Lower 95% (mm^3)	Upper 95% (mm^3)
HE	LD	1.164	0.286	4.080	<.001*	0.466	1.862
HE	ZIR	0.413	0.286	1.450	.329	−0.285	1.111
LD	ZIR	−0.751	0.286	−2.630	.033	−1.449	−0.053

HE, human enamel; LD, lithium disilicate; ZIR, zirconia

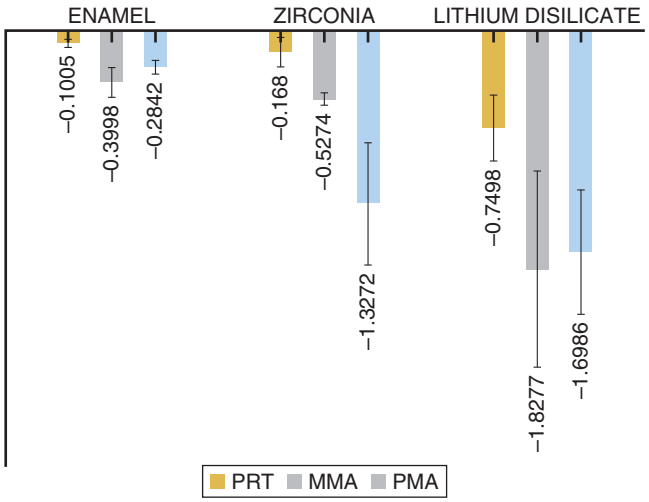

Figure 4. Substrate volumetric abrasion (mm^3). Grouped by antagonist. Volumetric mean wear with standard error mean of substrate wear. MMA, milled polymethyl methacrylate; PRT, printed; PMA, processed polymethyl methacrylate.

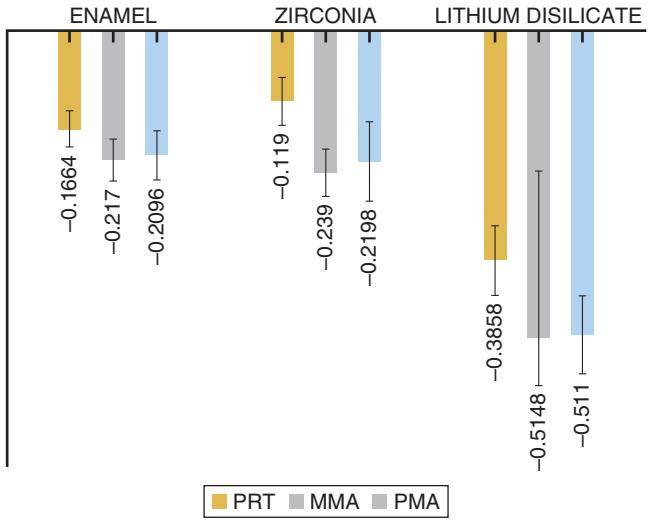

Figure 5. Antagonist volumetric abrasion (mm^3). Grouped by antagonist. Volumetric means wear with standard error mean of antagonist wear. MMA, milled polymethyl methacrylate; PRT, printed; PMA, processed polymethyl methacrylate.

Table 3. Results of two-way analysis of variance (ANOVA) of volume loss of antagonist materials

Source	Number of Parameters	Degree of Freedom	Sum of Squares (mm^3)	F Ratio	*P*
ANT	2	2	0.759	26.533	<.001*
SUB	2	2	0.091	3.170	.054
SUB×ANT	4	4	0.012	0.214	.929

ANT, antagonist; SUB, substrate.

(*P*>.05). The results of the post hoc Tukey pairwise comparison test on the influence of volume loss of the antagonist material on the antagonist wear (Table 4) showed that lithium disilicate (LD) had significantly more volume loss than human enamel and zirconia (ZIR) (both *P*<.01). Figure 5 summarizes the means and standard errors of the group, illustrating this significant increase in wear associated with lithium disilicate (LD). It also revealed that the group of zirconia and print resin (ZIR/PRT) was significantly different from lithium disilicate with both processed polymethyl methacrylate (PMA) and milled polymethyl methacrylate (MMA).

DISCUSSION

The volumetric and vertical wear of milled and printed occlusal device materials was measured against various antagonist materials in an in vitro environment. The null hypothesis that the volumetric wear of the occlusal device material would not be influenced by the materials used was rejected because the manufacturing process and composition significantly influenced the volumetric wear of the occlusal device materials (*P*<.05). The differences are evident in Figures 6 and 7, which show macro images illustrating the occlusal device materials wear patterns. Printed materials exhibited the least mean wear. Furthermore, certain substrate and stylus combinations showed variation in the volumetric wear rate of occlusal devices. Among the antagonists, lithium disilicate (LD) caused the most wear on the milled polymethyl methacrylate (MMA) substrate material (group: LD-MMA). This result differed from the wear observed in the human enamel against the printed resin (HE-PRT group). However, lithium disilicate (LD) demonstrated the highest wear when tested against the other antagonist materials compared with zirconia (ZIR) and human enamel (HE). This finding was consistent with those of other studies[17,18] reporting higher abrasive wear in lithium disilicate because of its lower fracture toughness compared with zirconia, making it less susceptible to crack growth and fatigue.[18,19]

Previous studies have investigated the effect of different antagonists opposing occlusal device materials.[5,13,25] Reyes-Sevilla et al[25] reported that an occlusal

Table 4. Results of Tukey pairwise comparison tests on influence of antagonist material on antagonist wear volume

ANT	-ANT	Difference	Std Error	t Ratio	*P*	Lower 95%	Upper 95%
LD	HE	−0.273	0.044	−6.250	<.001*	−0.380	−0.166
LD	ZIR	−0.278	0.044	−6.370	<.001*	−0.385	−0.171
HE	ZIR	−0.005	0.044	−0.120	.993	−0.112	0.102

ANT, antagonist; HE, human enamel; LD, lithium disilicate; ZIR, zirconia.

Figure 6. Macro images demonstrating material wear. Captured using a macro lens and auxiliary lens. Original magnification not precisely determined. A, PMA. B, MMA. C, PRT.

Figure 7. Macro images demonstrating material wear. Captured using a macro lens and auxiliary lens. Original magnification not precisely determined. A, PMA. B, PRT.

device fabricated via the additive manufacturing process experienced less wear than those made using subtractive methods. The materials studied included NextDent Ortho Rigid, which is a 3D printed resin based on a monomer primarily composed of acrylic ester,[33] and 2 types of polymethyl methacrylate with different manufacturing processes. The ProArt CAD is a milled process from a clear disk of polymethyl methacrylate material[32] and Vitacrilic Clear, which is a conventionally polymerized polymethyl methacrylate.[34] Prpic et al[5] reported that NextDent Ortho Rigid has the highest Vicker hardness value when compared with 5 other 3D printed occlusal device materials.

Furthermore, previous studies have provided relevant estimates of the degree of conversion of conventionally processed polymethyl methacrylate and printed resin.[9,10] In a recent study comparing SLA-printed, MSLA-printed, and heat-polymerized polymethyl methacrylate for occlusal devices, conventional heat-polymerized polymethyl methacrylate achieved a degree of conversion of approximately 95%, whereas SLA- and MSLA-printed resins reached around 58% after post-polymerizing.[9] Nonetheless, wear resistance is determined by multiple factors beyond the degree of conversion.[11] The most important structural difference between printed resin and polymethyl methacrylate is the crosslinking process of the printed occlusal devices.[17] Crosslinking is a chemical reaction that establishes connections between polymer chains, subsequently elevating molecular weight.[17] This distinction may explain the observed reduced wear in the printed specimens. These findings support the need to tailor material selection to the clinical function of the device. Devices for patients with parafunctional habits such as bruxism may require materials with high wear resistance, whereas devices for temporomandibular disorder management may benefit from greater resilience or flexibility.[7,18] Furthermore, occlusal devices are also indicated for managing unstable occlusion. Some designs are appropriate for specific functional patterns, occlusal relationships, including occlusal schemes, and offer distinct mechanical behavior and load distribution characteristics.[24] These factors should be considered when selecting the material for an occlusal device.

The Oregon Health Sciences University (OHSU) mastication wear machine, designed to replicate clinical usage, was used in this experiment. The machine had been calibrated according to the manufacturer's recommendations before the experiment and has been tested for 50 000 cycles with dental composite resins, equivalent to 6 months to 1 year of clinical wear.[31] Such testing provides in vitro conditions that provide consistent and controlled comparisons between materials. Although these conditions cannot fully replicate the complex oral environment observed in in vivo studies, they still offer valuable insights into the relative performance of materials.[4,30] This machine applied a 50-N load at the end of each mastication stroke,[38] as recommended by Grymark et al.[8] Artificial saliva (Artificial Saliva Medical & Dental; Pickering Laboratories, Inc) formulated for dental research was used as a lubricant.

Limitations of the study included potential data collection errors because of surface reflection during scanning.[36] It has been reported that the spray used to improve the scanning process can create a coating layer thickness of approximately 2 µm.[35,37] The present research adhered to the manufacturer's recommendations.[33] Ateş et al[13] reported that among the additive manufacturing process for occlusal devices, the horizontal orientation had higher volume loss and wear depth than the vertical and diagonal orientations. Further research and prospective clinical trials are needed for the long-term efficacy of printed occlusal devices.

CONCLUSIONS

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

1. The manufacturing method and composition of the material significantly affected the wear rate of occlusal devices.
2. Printed resins showed the least amount of wear compared with milled and conventionally processed polymethyl methacrylate.
3. Although the manufacturing process of occlusal devices did not significantly affect the wear rate of antagonists, lithium disilicate was found to have the most wear compared with zirconia and enamel.

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