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In Vitro Static and Fatigue Behavior of Ceramic Occlusal Veneers Using CAD/CAM

Keywords

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ABSTRACT

To evaluate fracture resistance of occlusal veneers made of glass-ceramic and zirconia with and without fatigue. Occlusal overlays (N=80; n=10 per group) were milled out of CAD/CAM materials, namely: a)LD:Lithium disilicate glass ceramic, b)LDS:Lithium-disilicate-strengthened aluminosilicate glass ceramic, c)ZLT:Zirconium dioxide ceramic and d)ZMT:Zirconium dioxide ceramic. The overlays were cemented on polymeric duplicates, randomly distributed to aging or non-aging conditions and loaded until fracture. Ultimate catastrophic failure strength(F_{max}*) and Initial crack formation load(*$F_{initial}$*) values were analysed using two-way ANOVA. For *$F_{initial}$*, material type and aging and their interaction resulted in significant values (p =<0.001).* $F_{initial}$ *mean±SD values ranged from ZMTa (593 N ±205 N) to LDSb (118 N ±42 N). As for *F_{max}*, the material type significantly affected the outcome (p<0.001), while aging type did not show an influence (p=0.795). The non-aged *F_{max}* specimens values presented were: LDSa (877 N ±253 N)<LDa (2029 N ±412 N)<ZLTa (2049 N ±379 N)<ZMTa (2144 N ±333 N), LDSa being significantly lower (p<0.001). The aged *F_{max}* values were: LDSb (1313 N ±599 N)< ZLTb (1715 N ±453 N)<ZMTb (2018 N ±300 N)<LDb (2134 N ±289 N). LDS yielded significantly lower *F_{max}* values without and non-significant less favourable results with aging. The mechanical properties following aging and lack of additional firing makes LDS an interesting restorative material for clinical application.*

INTRODUCTION

Since the introduction of the first all-ceramic products in the mid 1990s, the popularity of monolithic ceramic restorations using computer-aided design and computer-aided manufacturing (CAD/CAM) techniques has been risen.[1,2] This technique allows access to the application of new high-performance materials using faster and cost-efficient digital clinical workflows. As a result, many different machineable materials have been produced in the last decades, such as nanocomposites, polymer-infiltrated ceramics, leucite reinforced glass-ceramics, zirconia oxides, zirconia reinforced glass-ceramics or lithium disilicate reinforced glass-ceramics.[2] The material groups were used in the production procedures of chairside partial or full-contoured, single-unit, and multiple-unit veneers, crowns or fixed dental prostheses (FDPs).[3-5] The advantages of such digitally processed restorations are an aesthetic favourable appearance,[6] accurate marginal adaptation,[7,8] and a cost and time efficient production workflow.[8-11]

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All-ceramic glass-ceramics have been established in dentistry for decades because of their transparent behavior, low thermal conductivity, biocompatibility, and simple handling.[12] One dental ceramic in particular, lithium disilicate (LD), earned high recognition mostly due to its great clinical performance[3,4,5,13,14] and acceptance by patients, technicians, and clinicians.

Although the treatment with all-ceramic restorations grant considerable benefits, such as better optical performance, adhesion, less plaque retention over the conventional metal-ceramic restorations, the clinical evidence for long-term survival and complication rates are limited.[12,15] Nonetheless there are clinical studies, which show highly promising 5 and 10 years clinical follow-up performances of monolithic ceramic FDPs of 97.3% and 83.5% respectively,[3,4,5,15] especially in the anterior region.[16,17]

Manufacturers of newly introduced lithium disilicate reinforced lithium aluminosilicate glass-ceramic (LD-LAS) promise same benefits (good aesthetic properties, adhesion) and indication fields (tooth and implant-borne partial and full crowns and FDP's) as LD ceramics, showing comparable flexural strength tests results.[18] LAS exhibits a flexural strength of 100-250 MPa and a fracture toughness of 1–1.5 MPa_√m, which in combination with its low thermal expansion and transparency[19]. The reinforcement of LAS with LD can increase its flexural strength by up to 50%,[18] making it a high load-bearing material with aesthetic properties.[19] Moreover, one of the most remarkable clinical advantage of LAS compared to the other CAD/CAM ceramics is the block milling in a fully crystallized state, does not require additional firing and immediate seating after milling and polishing. The newly developed LAS is available in a wide colour range in accordance with the classic VITA Tooth Shade Guide (VITA Zahnfabrik, Bad Säckingen, Germany) in a high or low translucency form, which grants an optimal tooth-like appearance. Its chair-side workflow and aesthetic properties could make this freshly released dental ceramic an advantageous alternative to common glass ceramics.

There are some acceptable *in vitro* study results regarding fracture resistance;[19] however, evidence for laboratory and clinical performance is very limited for the LD-LAS-ceramic CAD/CAM material. The purpose of this *in vitro* study was therefore to compare this glass-ceramic with established CAD/CAM ceramics and to assess the influence of fatigue conditions simulation on its *in vitro* performance, as they influence the long-term survival rate of ceramic and should be conducted prior to clinical trials.

The null hypothesis of this study was that the choice of the material and aging method has no effect on the fracture resistance of the materials.

MATERIALS AND METHOD

TOOTH PREPARATION

A natural intact one-rooted upper third molar was obtained from the university bank of teeth for the design of the root duplicates and the occlusal veneers. The tooth surface was scanned (3Series, Dental Wings, Straumann, Basel, Switzerland) and afterwards sectioned at the cementoenamel junction using an electrical precision diamond wire saw (Well; Walter Ebner, Le Locle, Switzerland) at 250 rpm, with a wire diameter of 0.17 mm and 30 μm roughness under constant water cooling. The surface of the root was manually polished using up to #2400 grit silicon carbide paper (Struers, Willich, Germany) under constant water cooling until a plain surface was obtained. Eighty polymeric duplicates of the root surface were fabricated using a polyvinyl chloride (PVC) auto-polymerizing acrylic resin (Scandiquick, Scandia, Hagen, Germany) and a silicon replication key (Optosil, Kulzer, Germany). One-third of the apical part of the duplicates was thereafter embedded in an acrylic block (FiltekTM Supreme XTE Flowable Composite, 3M ESPE, St. Paul, MN, USA) allowing their occlusal surface exposed for bonding purposes and was needed as the supporting structure for subsequent mechanical test.

OCCLUSAL VENEER PREPARATION

After scanning of the natural occlusal tooth surface before cutting, the specific CAD (Dental Sytem, 3Shape, Copenhagen, Denmark) data of the constructed three-dimensional (3D) occlusal veneer were then exported as a stereolithography (STL) file and sent to CAD specialized dental technician in a dental laboratory. The technician imported the STL file into a rapid prototyping (RP) system (Dental System, 3Shape, Copenhagen, Denmark), which can be used to design and manufacture on- and overlay restorations. The occlusal veneers have been designed to fit perfectly on the polymer duplicate and to resemble a natural upper 3rd molar. The materials used for the overlay specimens (N=80) in this study were: a) LD: Lithium disilicate glass ceramic (IPS e.max CAD, Ivoclar Vivadent, Schaan, Lichtenstein), b) LDS: Lithium-disilicate-strengthened aluminosilicate glass ceramic (N!ce, Straumann, Basel, Switzerland), c) ZLT: Zirconium dioxide ceramic (IPS e.max ZirCAD LT, Ivoclar Vivadent, Schaan, Lichtenstein) and d) ZMT: Zirconium dioxide ceramic (IPS e.max ZirCAD MT, Ivoclar Vivadent, Schaan, Lichtenstein). After milling of the occlusal veneers (thickness: 1.5 mm) using a milling machine (PrograMill; Ivoclar, Schaan, Liechtenstein), LD and ZLT/ZMT were sintered to full density according to manufacturer's instructions (Programat CS 2, Ivoclar Vivadent) and (Programat S1 1600, Ivoclar Vivadent). Finally the occlusal veneers were glazed using a powder-liquid mix applied by brush (Vita Akzent; Vita Zahnfabrik) and underwent glaze-firing. Information regarding materials, material composition and mechanical properties are shown in Table 1.

Table 1. Materials and their specifications provided by the manufacturers.

Product, manufacturers	Material Classification	Weight in % Composition	Flexural strength (MPa) given by manufacturers
IPS e.max CAD, Ivoclar Vivadent Schaan Liechtenstein	Lithium disilicate ceramic	57-80 SiO_2, 11-19 Li_2O, < 5 Al_2O_3, < 13 K_2O, < 8 ZnO, < 11 P_2O_5, < 8 ZrO_2, < 5 MgO, < 8 other oxides	360
N!ce, Institut Straumann Basel Switzerland	Lithium disilicate strengthened lithium aluminosilicate glass-ceramic	< 70 SiO_2, ~11 Li_2O, ~11 Al_2O_3, < 3 K_2O, ~2 Na_2O, < 8 P_2O_5, < 0.5 ZrO_2, < 2 CaO, < 9 other oxides	350
IPS e.max ZirCAD LT, Ivoclar Vivadent Schaan Liechtenstein	Zirconium oxide ceramic, low translucency	88.0 - 95.5 ZrO_2, >4.5-≤6.0 Y_2O_3, ≤5.0 HfO_2, ≤1 Al_2O_3, ≤1.0 other oxides	1200
IPS e.max ZirCAD MT, Ivoclar Vivadent Schaan Liechtenstein	Zirconium oxide ceramic, medium translucency	86.0 - 93.5 ZrO_2, >6.5 - ≤8.0 Y_2O_3, ≤5.0 HfO_2, ≤1 Al_2O_3, ≤1.0 other oxides	850

SURFACE CONDITIONING PROTOCOL

All overlay veneers were conditioned according to the manufacturer's recommendations. LD and LDS specimens were etched with 5% hydrofluoric acid (IPS Ceramic Etching Gel, Ivoclar Vivadent) for 20 seconds, rinsed with water for 60 seconds and dried with air-flow using a syringe. The specimens were then stored in an ultra-sonic alcohol bath for five minutes. Afterwards a thin layer of silane (Monobond Plus, Ivoclar Vivadent) was applied for 60 seconds and air-thinned on the overlay veneers and root duplicates. Finally the surfaces were coated using a light-cured bonding agent (Heliobond, Ivoclar Vivadent) with subsequent removal of the excess bonding material.

Both ZLT and ZMT specimens were conditioned using a different protocol. The first step was roughening the luting surface for 5 seconds with aluminium-oxide air-abrasion (CoJet, 50 µm 1,2 bar, 3M ESPE, St. Paul, USA) at the distance of 10 mm, which was followed by water rinsing and drying with air-flow. After storing the specimens in an alcohol ultra-sonic bath for five minutes and dried. A thin layer of ceramic primer (Clearfil Ceramic Primer, Kuraray, Tokyo, Japan) was applied for 20 seconds and air-thinned.

The polymeric duplicate was not treated further. The conditioning protocol was conducted according to the manufacturer.

CEMENTATION PROTOCOL

The cementation of the occlusal veneers to the polymer duplicates was conducted with a dual-cured resin-based cement (RelyX Ultimate, 3M ESPE, St. Paul, USA) for LD and LDS veneer overlays, using an adhesive cementation load of 25 N using an ultrasonic device (SONICFlex, Kavo, Biberbach, Germany). The excess cement was removed and a layer of oxygen-inhibiting gel (Oxyguard, Kuraray, Tokyo, Japan) was applied around the margin of the reconstruction. Light-curing (Bluephase, Ivoclar Vivadent, Schaan, Liechtenstein) was performed for 40 seconds from each side.

ZirCAD LT and ZirCAD MT were bonded with a self-curing one-step resin cement (Panavia 21, Kuraray, Tokyo, Japan), excess was removed directly after the placement and a layer of oxygen-inhibiting gel (Oxyguard, Kuraray, Tokyo, Japan) was applied around the margin of the reconstruction (*Figure 1*).

CHEWING SIMULATION

Specimens were randomly allocated to two different aging protocols: a) immediate fracture resistance test without aging, b) delayed fracture resistance test after chewing simulation. After finishing the luting steps, groups of each material, namely LDb, LDSb, ZLTb, and ZMTb were mounted into a custom-made chewing simulator (1'200'000 cycles, 49 N force and 1.67 Hz loading frequency, custom-made, University of Zurich, Switzerland).[20] The antagonist was a corrosion-free

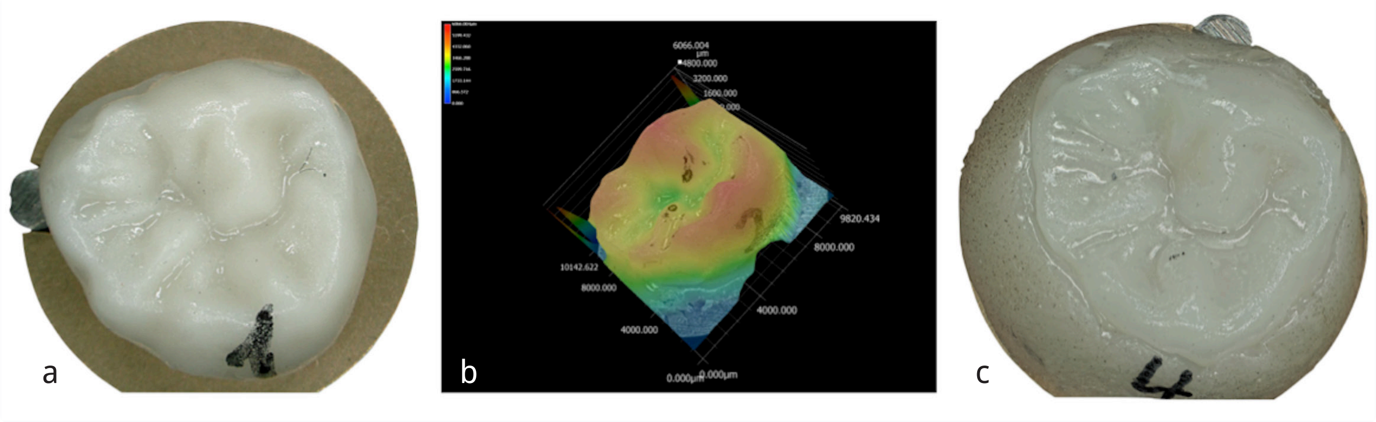

Figure 1. a) Setup of the specimen cemented onto the polymeric duplicates before chewing simulation. b) the surface analysis after chewing-simulation using a digital microscope (VHX 2000D, Keyence, Osaka, Japan). c) the specimen embedded in epoxy resin ready for fracture resistance test.

steel indenter with a diameter of 8 mm, force was applied perpendicular to the centre without sliding movements of the occlusal veneers. The center was chosen as the meeting point of the mesiopalatinal and distobuccal enamel cusps. The occlusal region was placed in the middle of the fossa. But the anatomical form was not established considering the form of the sphere. The specimens were kept dry until resistance test, which was conducted after the chewing simulation, after 1 week.

FRACTURE RESISTANCE EVALUATION

All non-aged (LDa, LDSa, ZLTa, and ZMTa) and aged (LDb, LDSb, ZLTb and ZMTb) specimens were loaded axially to fracture using a universal strength-testing machine (Zwick / Roell Z010, Zwick, Ulm, Germany) with a speed of 1 mm/min. Within the loading process, two values were documented for each specimen: $F_{initial}$ and F_{max}. $F_{initial}$ describes the force needed to irreversibly deform the restoration. F_{max} defines the final and highest force needed for fracture of the specimen. The force was applied using an indenter at the centre of each ceramic CAD/CAM occlusal veneer; data was collected from the universal testing machine and statistically evaluated.

STATISTICAL ANALYSIS

All analyses in this report were performed with the statistics software R, version 3.5.0 (R Development Core Team, Vienna, Austria). The nonparametric two-way ANOVA by Brunner and Munzel[21] was used as overall test to assess the global differences in medians as both outcomes $F_{initial}$ and F_{max} were heteroscedastic and not normally distributed. If a factor or an interaction showed significance in the overall test, Exact Wilcoxon Rank Sum tests were conducted as *post hoc* tests to assess local differences in medians. Throughout, p-values smaller than or equal to 0.05 were considered statistically significant. Furthermore, p-values for *post hoc* tests were corrected for multiple testing with Holm's method.[22]

RESULTS

FATIGUE RESISTANCE

All the specimens underwent chewing simulation, which resembled five years of intraoral wear *(Figure 2)*.

NON-AGED SPECIMEN

Regarding the $F_{initial}$ values of the non-aged specimens, ZMTa (593 ± 205 N) showed the highest mean values against deformation, followed by LDa (384 ± 162 N), ZLTa (539 ± 347 N), and finally LDSa (197 ± 106 N). Only the differences between LDSa and ZLTa (p=0.048) and LDSa and ZMTa (p=0.01) were significant for the non-aged probes *(Table 2)*.

Out of the four groups of the pristine and non-aged ceramic materials, ZMTa (2144 ± 333 N) showed the highest values for F_{max}, followed by ZLTa (2049 ± 379 N) and LDa (2029 ± 412 N). The differences of the mean values were not statistically significant (p=1). On the other hand, the median value of F_{max} for LDSa (877 ± 253 N) was significantly lower than the ones of the other pristine materials: compared to ZLTa (p=0.0001), LDa (p=0.0002), and ZMTa (p=0.0005).

SPECIMEN AGED IN THE CHEWING SIMULATOR

The data of the aged specimens F_{max} values did not significantly differ from each other (p>0.05) and presented values in the following ascending order LDSb (1313 ± 599 N) < ZLTb (1715 ± 453 N) < ZMTb (2018 ± 300 N) < LDb (2134 ± 289 N). As for $F_{initial}$, the results presented in the following order: LDb (461 ± 222 N) > ZMTb (350 ± 240 N) > ZLTb (202 ± 90 N) > (118 ± 42 N). Out of the possible combination comparisons, only the combinations of LDb with ZLTb (p=0.03) and LDb with LDSb (p=0.03) were statistically significant.

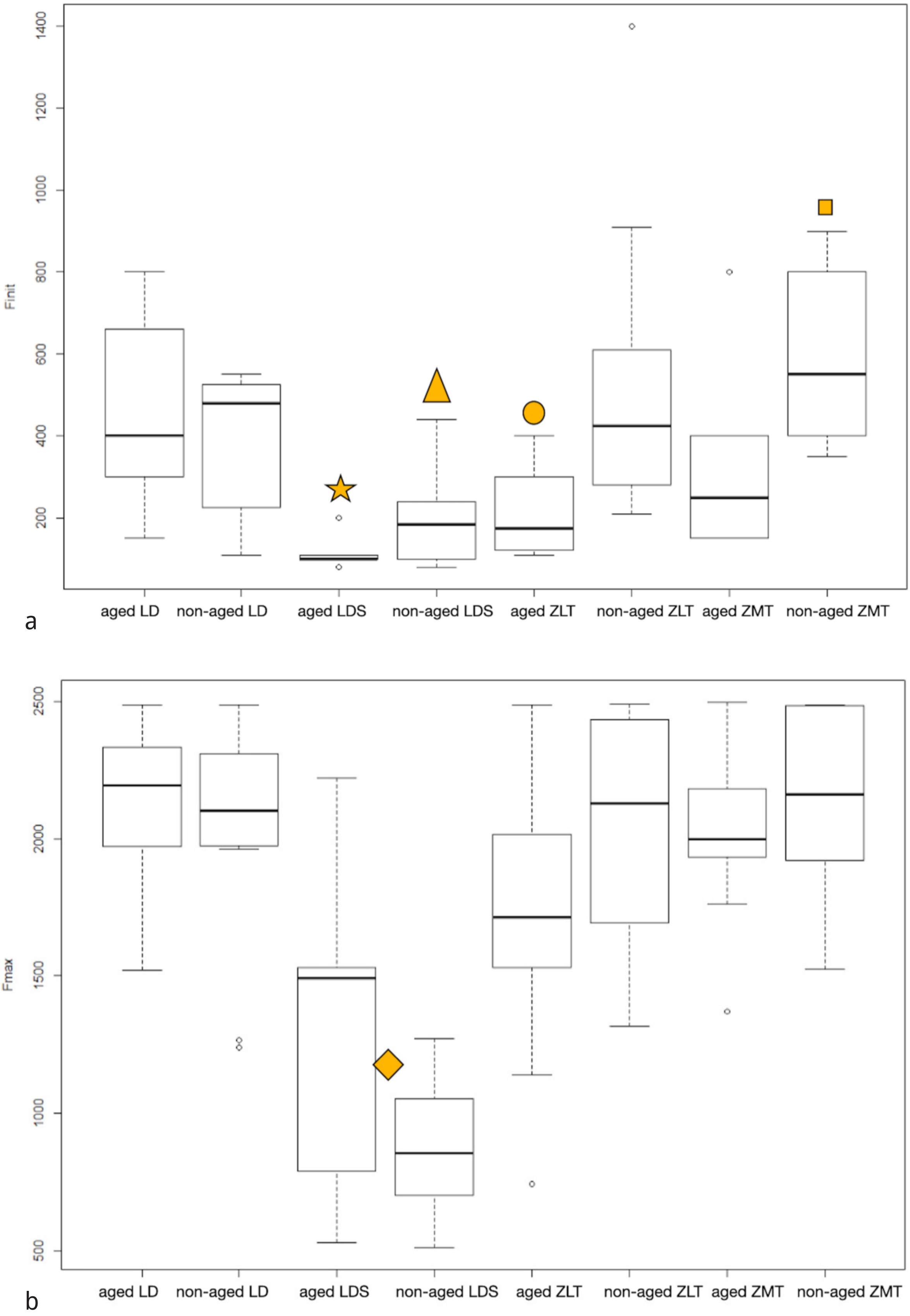

Figure 2. The force required to a) irreversibly deform the material ($F_{initial}$); and b) the load-bearing capacity (F_{max}) for all aged and non-aged dental restorative materials groups (LD, LDS, ZLT and ZMT) used in this study in Newton (N). Significance including highest (■), lowest(★), second (▲) and third (●)lowest combination values of material and aging. ◆: aged and non-aged LDS group showed significance compared to all other materials groups.

Table 2. The force required to irreversibly deform the material ($F_{initial}$) and the fracture (F_{max}) for all dental restorative materials used in this study with different aging processes: median and mean values with standard deviation (SD) in Newton (N).

		$F_{initial}$ [N]	F_{max} [N]
Material	**Aging**	***Mean* ± SD**	***Mean* ± SD**
E.max	Dry	384 ± 162	2029 ± 412
E.max	CS	461 ± 222	2134 ± 289
N!ce	Dry	197 ± 106	877 ± 253
N!ce	CS	118 ± 42	1313 ± 599
ZirCAD LT	Dry	539 ± 347	2049 ± 379
ZirCAD LT	CS	202 ± 90	1715 ± 453
ZirCAD MT	Dry	593 ± 205	2144 ± 333
ZirCAD MT	CS	350 ± 240	2018 ± 300

Abbreviation: CS (Chewing simulation)

DRY VERSUS CHEWING SIMULATOR

For $F_{initial}$, both, material type and aging, had a significant impact on the results ($p<0.001$), while for F_{max} the material type significantly affected the outcome ($p<0.001$), while aging type did not show an influence ($p=0.795$). For $F_{initial}$ values, the non-aging values yielded higher values than aging, except for the material LD the difference was not statistically significant. As for the interaction of material and aging method, significant combinations could be found comparing: ZMTa had significantly higher values than ZLTb ($p<0.0001$), LDSb ($p=0.04$), and LDSa ($p=0.1$). ZLTb performed worse than ZLTa ($p=0.02$), LDSa had significantly lower values than ZLTa ($p=0.048$). Finally the group with the lowest values LDSb showed significantly lower resistance compared to ZMTa ($p=0.04$), ZLTa ($p=0.02$), and LDa ($p=0.03$).

DISCUSSION

This study was conducted to evaluate the fracture strength of occlusal veneers of various glass-ceramic and zirconia materials using computer-aided design and manufacturing (CAD/CAM) technologies with and without chewing simulation. The null hypothesis was not rejected for the influence of the aging method in terms of F_{max}. However, the null hypothesis was rejected for influence of the choice of both, the material and aging method for $F_{initial}$, and for the material investigating F_{max}.

The choice of cements depended on the materials studied and the manufacturer's recommendations. The results revealed very high fracture resistances for G4: ZMT; G3: ZLT; G1: LD as previously reported in various studies analysing occlusal veneers.[23-27] There were no significant differences between the oxide ceramics and the LD ceramic, although the manufacturer (IPS Ivoclar Viavadent) specifies large discrepancies in mechanical toughness among these three materials (*Table 1*). This issue has also been controversially discussed in former studies, presenting fracture resistance values ranging from 701 to 2639 N.[23-27] This contradictory result might be explained by the choice of a polymeric duplicate, embedded in epoxy resin, instead of human tooth with a dentin or enamel occlusal surface, as the abutment has been proven to have a significant impact on the fracture resistance either due to its elasticity module or the bonding strength to the restoration.[23,24,28-30] Another possible reason for this phenomenon might be the use of a different zirconium dioxide product with a different composition (Vita YZ HT, Vita Zahnfabrik).[23,24] F_{max} was comparable to the outcome with recent similar studies, where the restorations were bonded to teeth with a thickness of 0.5 mm and 1 mm.[23,24,29] Other recent studies also reported much higher fracture rates ranging from 2895 N to 4173 N.[30] Reason for that might be the selection of the abutment, as in this present study the specimens were embedded in epoxy resin, which has a similar elastic modulus as hydrated dentin and therefore is able to mimic clinical failure modes,[31] tooth selection, tooth preparation or thickness of restoration.[28,32] The polymer root duplicate has not been conditioned, since the bonding strength of resin-based cement to polymer material is already more than necessarily strong. The cementation surface has been kept polished.

The aging process, simulating five years of function, did not lead to any premature failure of any specimen, which appears to be applicable for the long-term stability in clinical application.[20,33-35] Furthermore, the aging condition did not significantly influence the load-bearing capacities for F_{max} of the investigated occlusal veneers, partly confirming outcomes of recent *in vitro* tests, in which specimens even reached higher fracture values after thermodynamic loading.[29]

For the non-aged LD-LAS the results of the present study showed significantly lower values, compared to the other investigated ceramics, which partly rejects the first null hypothesis of exhibiting no differences between all the investigated ceramics. However, the fracture resistance of all the occlusal veneers, which underwent the chewing-simulation did not significantly differ from one another. This outcome partly confirms the first null hypothesis as it was expected due to previous laboratory research[18,19] and the manufacturers specifications (*Table 1*). Reasons for the lower load-bearing capacity of non-aged LD-LAS can be explained by its material properties, regarding composition, manufacturing and different heat treatment profiles.[18,36,37] The higher content of aluminosilicate at the expense of LD in addition to the lack of hardening throughout firing processes seems to lower mechanical performance in non-aged condition.

Physiological chewing forces can range from 200 N to 540 N but reach up to 800 N in the posterior region in patients suffering from bruxism.[34] With aged LDS; and non aged LDS yielding fracture resistances of 1313 ±599 N and 877 ±253 N for F_{max} respectively, it might be contraindicated to clinically apply LD-LAS, with similar dimensions as it was prepared in this present study, in form of occlusal veneers in patients with parafunctional grinding of the teeth.

Regarding the $F_{initial}$ values, resembling the necessary strength for initial irreversible deformation of the specimen, all the non-aged occlusal veneers tend to have higher values than the mechanically aged ones, but only the group aged ZLT; yielded significantly lower data compared to the non aged ZLT. This difference indicates a sign of wear from the chewing simulation, which might be explained by subcritical damage induced by repeated mechanical stress.[38] ZirCAD LT and N!ce seem to be more susceptible to fatigue than their untouched counterpart. Different materialistic features, material compositions or production processes might be reasons for this outcome.[18,39] Especially the lower content of the main structural components zirconium dioxide and LD and thereby related higher content of additional components for aesthetical reasons.

Within the limitation of this study, the evaluation of both, F_{max} and $F_{initial}$, values indicated, that the mechanical performance of LD-LAS was significantly lower than of LD and the two different types of zirconium dioxides. Although we found evident statistical significance in this present study, the impact of these results is very difficult to apply in a clinical scenario, as there are various limitations of this *in vitro* mechanical research.[40] Further clinical studies should be conducted with higher statistical power, may indicate significantly worse performance of LDS. Nevertheless with this material could considered advantageous in the clinical workflow because of lack of sintering. Furthermore, in cases of patients with non-physiological biting forces, it might be contraindicated to apply LD-LAS in the posterior region due to its lower load-bearing capacity. Restorative applications and clinical guidelines should be further investigated.

CONCLUSIONS

From this study, the following could be concluded:

1. Except for LDS, all investigated monolithic ceramic occlusal veneers using CAD/CAM technology yielded clinical acceptable results for clinical application due to their fatigue and fracture resistance. Nonetheless, the mechanical properties and the efficient CAD/CAM workflow of LDS makes it an interesting restorative material for clinical application, especially due to the lack of additional firing
2. Lithium disilicate reinforced lithium aluminosilicate could be considered as an alternative due to its time efficient workflow. However, the application of this material in the posterior region needs to be carefully considered in case of exceeded bite forces.

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DISCLOSURE

The authors declare that they have no conflict of interest.

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