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EFFECTS OF DENTAL TISSUE SUBSTRUCTURE AND SIZE ON FRACTURE STRENGTHS OF LITHIUM DISILICATE AND ZIRCONIA CERAMICS

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Abstract
We aimed to assess the effects of standard resin preparation models with five different thicknesses of occlusal surface on the fracture strengths of zirconia (ZrO2) and lithium disilicate glass ceramics. The specimens of 10 first maxillary molars collected between January 2019 and January 2020 were selected. Standard mathematical models were formed after scanning the resin matrices using software. The full crowns with five different thicknesses of occlusal surface were established, among which the molar specimens prepared by ZrO2 glass ceramic composites alone were assigned into ZrO2 group (n=5, 40 specimens) while those prepared using ZrO2-lithium disilicate glass ceramic composites were allocated into ZTCLDC group (n=5, 40 specimens). When the thickness of glass-ceramic full crowns was 0.5, 0.8, 1.0, 1.2 and 1.5 mm, the fracture load of the specimens in ZTCLDC group was not significantly different from that in ZrO2 group, and there was no significant difference in the three-point flexural strength between ZTCLDC group and ZrO2 group ($P>0.05$). The fracture toughness was not significantly different between the two groups in the case of the thickness of glass-ceramic full crown at 0.5, 0.8, 1.0, 1.2 and 1.5 mm ($P>0.05$). The thickness was positively correlated with fracture load, three-point flexural strength and fracture toughness ($P<0.05$). The fracture strength of lithium disilicate and ZrO_2 ceramics is directly proportional to the thickness of ZrO_2 and ZTCLDC crowns.

Keywords: Ceramics. Fracture strength. Glass. Lithium. Tooth tissue.

1. Introduction

Dental bonding, surface treatment and ceramic thickness are primary factors influencing the fracture resistance of implant dentures (ceramic dental crowns) (Łagodzińska et al. 2023). The thickness of occlusal surface has been strictly controlled (mostly within 1.5-2.0 mm) by most of dental all-ceramic material manufacturers (Gorman et al. 2019; Kraipok et al. 2021). With favorable biocompatibility, chemical stability and beautiful appearance, ceramic materials are currently one of the key materials applied to dental restoration in clinical medicine, especially in the field of stomatology (Wang et al. 2023).

Glass ceramics have the advantages of both glass and ceramics, and its optical and mechanical properties are obviously better than those of the materials for metal-porcelain restoration (Zhang et al. 2023). The application of the latter is restricted owing to poor toughness and great brittleness, though it has once been the first choice for fixed dental restoration. Although glass-ceramic restoration has more obvious advantages in fracture strength and fracture toughness over those of traditional dental restoration (Meng et al. 2021), it remains to be urgently improved when applied in the field of stomatology due to the restriction of oral medical technology.

Aluminum oxide and zirconia (ZrO_2) ceramics possess excellent mechanical properties (Tribst et al. 2019; Tavares et al. 2020), but their application is restricted by insufficient translucency which is approximate to that of metals. Hence, they have been mostly applied to fixed partial dentures in the aspect of dental restoration. As for dental glass-ceramic materials, the strength of mica and aluminum oxide glass ceramics can be effectively improved by the toughening brittleness of ZrO_2 (Li et al. 2021). Meanwhile, the mechanical strength and translucency of experimental lithium disilicate glass ceramic added with ZrO_2 (Pilecco et al. 2021), i.e. ZrO_2-lithium disilicate ceramic composite (ZTCLDC), are significantly enhanced. Nevertheless, the correlation between the thickness of occlusal surface and the fracture strength of ZTCLDC remains to be further explored.

Thereby motivated, we herein assessed the effects of standard resin preparation models with five different thicknesses of occlusal surface on the fracture strengths of ZTCLDC, aiming to prepare a potentially promising material for the field of dental restoration.

2. Material and Methods

Experimental materials

Hydrofluoric acid etching agent was provided by Bisco (USA). Variolink II resin cement and Monobond Plus silane coupling agent were purchased from iVoclar Vivodent (Switzerland). Spraying material was bought from VITA (Germany).

Experimental apparatus

The basic formula of new-type lithium disilicate glass ceramic is listed in Table 1. The experimental facilities included analytical balance (Mettler-Toledo, USA), 101A-1 electrothermal blast drying oven (Shanghai Laboratory Instrument Works Co., Ltd., China), and SX3-12-16 electric resistance furnace (Xiangtan Sanxing Instrument Co., Ltd., China).

Table 1. Ingredients of base glass in glass ceramic (mol/%).

SiO_2	LiO_2	Al_2O_3	K_2O	ZrO_2	P_2O_5	Others		
						CeO_2	CaO	MgO
66.00	27.00	2.00	1.80	1.50	1.20		0.5	

ZrO_2: Zirconia.

Digital abutment and dental crown models

Standard resin preparation models (Nissin, Japan) of 10 first maxillary molars (the dental crowns removed through orthodontic extraction were intact without cracks or caries) were constructed, where the width of cervical margin was 1.0 mm (circular shoulder), the aggregation angle of axial surface was 6°, the height of occlusal surface was 1.5 mm (reduced), and the thickness of occlusal surface was 0.5, 0.8, 1.0, 1.2 and 1.5 mm (cement space reserved, space size: 10 µm).

Methods for ZrO_2 group

The specimens in ZrO_2 group were prepared using IPS e.max Press material [material model: ECHT, transparency: high transparency A2, technical process: computer-aided design (CAD)/computer-aided manufacturing (CAM)] manufactured by iVoclar Vivodent (Switzerland).

Methods for ZTCLDC group

The resin matrices were scanned *via* software (3SHAPE, Denmark) to form a standard mathematical model. After the related data of designed digital abutments and dental crowns were input into CAD system device (CAD/CAM 2021 Chinese version), polymethyl methacrylate abutments and dental crowns with five different thicknesses (0.5, 0.8, 1.0, 1.2 and 1.5 mm) were fabricated using dental resin trays, followed by embedding and die casting. Later, the full crowns were bonded. Before bonding, each full crown was acid-etched using hydrofluoric acid (9.6%) for 20 s. Next, the ceramic surface was thoroughly washed for 1 min. The inner surface of each full crown was smeared with silane coupling agent and then air dried under natural conditions for 1 min. Subsequently, the glass ceramic crowns were bonded onto the polymethyl methacrylate abutments. After that, the composite resin was illuminated for curing (light intensity: 500 mW cm^{-2}, curing time: 30 s, compound angle: lips, tongue, middle and far end) after the excessive cement at the edge was removed. After 15 min, the crowns (after curing process) were perpendicularly embedded into the self-curing resin and then removed after cementation for 1 h. Finally, all the crowns subjected to the curing process were preserved in distilled water for 24 h.

The fracture resistance experiment was first conducted for all specimens after 10,000 thermal cycles (temperature: 5-55°CC, temperature holding time: 30 s, for artificial aging simulation) on a universal testing machine. Three-point contacts were established using stainless steel balls in the center of each dental crown (diameter of steel balls: 6 mm, descent speed of steel balls: 1 mm/min, and working direction: vertical stress load applied along the major axis of tooth body). Besides, polyethylene forming foils (foil thickness: 1 mm) were placed between the dental crown and loading ball to realize uniform pressure distribution. Next, the maximum load at the moment of crown fracture was recorded *via* intelligent test software (TestXpert II, ZwickRoell, Germany). After the fracture experiment on every molar was completed, the representative specimens were extracted through electron microscope scanning for the subsequent test and the analysis of crown fracture mode and fracture (observed under a stereomicroscope). After soaking in BioSonic UC 125H ultrasonic cleaner (Biokleen, USA) for 10 min, the specimens were taken out, blown dry and treated with metal spraying.

1) Flexural strength: The flexural strength of each specimen was tested through the three-point bending method in accordance with relevant standards of International Organization for Standardization 6872. The loading rate and span were 0.5 mm/min and 20 mm, respectively. The calculation formula was M three-point flexural strength = 3 $wl/2\ bd^2$, where w is the fracture load (N), l is the span width (mm), b denotes the specimen width (mm), and d stands for the specimen thickness (mm). 2) Fracture toughness: The fracture toughness was calculated through the following formula: $\mathrm{K_{IC}} = 0.16Hv \times \mathrm{a}^{1/2} \times (c/a)^{-3/2}$, where Hv represents the Vickers microhardness (load: 500 *gf*, loading time: 15 s), a stands for the average length of indentation diagonal [$(a_1 + a_2)/2$], and c is the average length of crack [$(c_1 + c_2)^{1/2}$]. The measuring equipment was HXD-1000TM digital microhardness tester (Shanghai Taiming Optical Instrument Co., Ltd., China). Five points from each specimen were measured, and the average value was calculated. Multiple comparisons were implemented for all data (analysis of variance and Tukey test). 3) Fracture load: The fracture load [$\mathrm{F}(u)$ value] was averaged.

Statistical analysis

An Excel database was established. The baseline information and research data of the two groups (5 molars in each group) were processed by SPSS 21.0 software (IBM Inc., USA). The χ^2 test was performed for numerical data. The mean difference between two specimens was tested by analysis of variance (*F* test) and expressed as ($\bar{x} \pm s$). Multivariate logistic regression analysis was performed. P<0.05 suggested a statistically significant difference.

3. Results

F*(u)* values of glass-ceramic full crowns with different thicknesses

When the thickness of glass-ceramic full crowns was 0.5, 0.8, 1.0, 1.2 and 1.5 mm, the fracture load of the specimens in ZTCLDC group was not significantly different from that in ZrO_2 group (P>0.05) (Table 2).

Table 2. Fracture loads of glass-ceramic full crowns with different thicknesses [n=5, (N)].

Group	0.5 mm	0.8 mm	1.0 mm	1.2 mm	1.5 mm	*t*	*P*
ZrO_2	683.47±111.03	1106.32±250.34	1337.21±198.65	1523.42±195.62	1825.64±334.67	116.04	0.000
ZTCLDC	700.54±112.39	1102.31±205.69	1340.68±221.36	1522.37±211.35	1792.65±284.68	117.52	0.000
t	0.265	0.030	0.029	0.009	0.184		
P	0.797	0.977	0.977	0.993	0.858		

ZrO_2: Zirconia; ZTCLDC: ZrO_2-lithium disilicate ceramic composite.

Three-point flexural strengths of glass-ceramic full crowns with different thicknesses

When the thickness of glass-ceramic full crowns was 0.5, 0.8, 1.0, 1.2 and 1.5 mm, the difference in three-point flexural strength was not significant between ZTCLDC group and ZrO_2 group (P>0.05) (Table 3).

Table 3. Three-point flexural strengths of glass-ceramic full crowns with different thicknesses [n=5, (MPa)].

Group	0.5 mm	0.8 mm	1.0 mm	1.2 mm	1.5 mm	*t*	*P*
ZrO_2	211.25±15.67	214.57±11.56	218.54±10.76	225.41±12.67	238.54±12.57	5.58	0.001
ZTCLDC	297.52±15.67	291.54±16.58	283.62±14.58	278.51±10.56	272.34±11.38	6.09	0.000
t	9.536	9.328	8.797	7.886	4.883		
P	0.000	0.000	0.000	0.000	0.001		

ZrO_2: Zirconia; ZTCLDC: ZrO_2-lithium disilicate ceramic composite.

Fracture toughnesses of glass-ceramic full crowns with different thicknesses

With the thickness of glass-ceramic full crowns at 0.5, 0.8, 1.0, 1.2 and 1.5 mm, there was no significant difference in the fracture toughness between ZTCLDC group and ZrO_2 group (P>0.05) (Table 4).

Table 4. Fracture toughnesses of glass-ceramic full crowns with different thicknesses [n=5, ($MPa \cdot m^{1/2}$)].

Group	0.5 mm	0.8 mm	1.0 mm	1.2 mm	1.5 mm	*t*	*P*
ZrO_2	2.43±0.55	2.51±0.53	2.58±0.56	2.92±0.58	3.34±0.57	4.46	0.003
ZTCLDC	3.06±0.57	3.18±0.58	3.24±0.55	3.48±0.56	4.32±0.58	7.08	0.000
t	1.948	2.089	2.005	1.701	2.952		
P	0.080	0.063	0.073	0.120	0.015		

ZrO_2: Zirconia; ZTCLDC: ZrO_2-lithium disilicate ceramic composite.

Multivariate analysis results of glass-ceramic full crown, flexural strength, F*(u)* value and fracture toughness

The abovementioned single factors with statistical significance (P<0.05) were incorporated into the multivariate logistic regression analysis. It was discovered that the glass-ceramic full crown was positively correlated with the flexural strength, F*(u)* value and fracture toughness (P<0.05) (Table 5).

Table 5. Multivariate analysis results of glass-ceramic full crown with flexural strength, $\mathrm{F}(u)$ value and fracture toughness.

Variable	*β*	*Standard error*	*Odds ratio*	P	*95% confidence interval*	
					Lower limit	Upper limit
Flexural strength	1.256	0.265	-0.113	0.126	0.186	0.569
Fracture load	1.869	0.326	-0.347	0.000	3.584	9.421
Fracture toughness	2.315	0.452	-0.329	0.000	4.152	8.675

4. Discussion

The application of ZrO_2 ceramic in clinical medicine has been explored for a long time. However, the translucency of ZrO_2 is low, equivalent to that of metals. Therefore, an appropriate amount of ZrO_2 has been added into lithium disilicate glass ceramic. The flexural strength of ZTCLDC declines with increasing ZrO_2 content (Gali et al. 2019; Elraggal et al. 2021). When the ZrO_2 content rises to 4%, the fracture toughness can reach up to 4.3 $MPa \cdot m^{1/2}$ after hot pressure casting, indicating that ZrO_2 can effectively improve the fracture toughness of lithium disilicate glass ceramic.

In this study, when the thickness of glass-ceramic full crowns was 0.5, 0.8, 1.0, 1.2 and 1.5 mm, no significant differences in the fracture load, three-point flexural strength and fracture toughness were observed between ZTCLDC and ZrO_2 groups ($P>0.05$), indicating that the fracture strength of pure ZrO_2 glass ceramic was basically identical to that of ZTCLDC of the same crown thickness, with similar fracture resistances. Nevertheless, as the thickness of glass-ceramic full crown increased gradually, the strength of both ZrO_2 glass ceramic and ZTCLDC were enhanced. In other words, the thickness of glass-ceramic full crown was larger at higher fracture load, three-point flexural strength and fracture toughness.

In natural dentition, the stress distribution in the chewing process may be remarkably influenced by the periodontal ligament around the root of tooth. However, the necessity of periodontal ligament simulation in the fatigue test remains controversial (Xiang et al. 2020). Periodontal ligament has been simulated using plastic cement, polyether, polysiloxane and other materials to realize the minimum range of motion when the optimal test load is reached (Nawafleh et al. 2020). Different degrees of motion are generated due to the differences in the physical and mechanical properties of such materials, so the study results deviate from the actual situation. Man-made periodontium was not used in this study, because single crown had the potential risk of movement (Ardakani et al. 2019; Jang et al. 2019; Li et al. 2020; Ji et al. 2021). Moreover, the motion direction of dental crown and abutment cannot be accurately controlled during stress loading.

In this study, the abutments and melting mold crowns in both ZrO_2 and ZTCLDC groups were prepared through the CAD/CAM technology to ensure the homogeneity and uniformity of each hot pressure cast structure. The occlusal force was relatively low when the thickness of glass-ceramic full crown was 0.5 mm, while the fracture load significantly increased at the thickness of 0.8, 1.0, 1.2 and 1.5 mm, showing significant differences compared with that at the thickness of 0.5 mm ($P<0.05$). Additionally, the fracture load, three-point flexural strength and fracture toughness had positive correlations with the thickness, since the occlusal force of teeth was usually dispersed on various teeth under normal physiological conditions. However, the dental crowns under mutual contact may be involved in the case of periodontium impairment or extreme factors. When the thickness of glass-ceramic full crowns was increased to 1.2 and 1.5 mm, the fracture load, three-point flexural strength and fracture toughness were still not statistically different ($P>0.05$), suggesting that no fracture risk was induced to ZTCLDC or ZrO_2 when the thickness of glass-ceramic full crowns was raised to 1.5 mm (Fan et al. 2021; Song et al. 2021; Türksayar et al. 2021). Hence, the fracture risk was not progressively increased when the above-mentioned two materials were used for the full crown restoration of the first maxillary molar and the thickness of dental crown prepared was controlled within 1.2-1.5 mm. The fracture analysis showed that the structures on the fracture surface of monolayer full crown of ZTCLDC and ZrO_2 were still uniform, without pores or large gaps. Meanwhile, the number of fractures mostly ranged from 2 to 3, and the fewer radial cracks contributed to a greater crown thickness. Given the miscellaneous construction of dental crowns in clinical practice, it is still necessary to evaluate the anti-fracture behaviors of monolayer full crowns more comprehensively (Ramenzoni et al. 2019).

5. Conclusions

In summary, the fracture strength of lithium disilicate and ZrO_2 ceramics is in direct proportion to the thickness of ZrO_2 and ZTCLDC crowns, that is, the thickness is greater at higher fracture load, three-point flexural strength and fracture toughness. In other words, the fracture resistance of ZrO_2 and ZTCLDC crowns will be strengthened if the thickness is increased. It is expected that the disadvantages of this study like small sample size and lack of data before and after hot pressure casting can be solved in the future.

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