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Original Article

Comparative Evaluation of Fracture Resistance and Failure Modes in Endodontically Treated Molars Restored with Zirconia Endocrown and Onlays

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Abstract

Introduction: Developments in dental materials, CAD/CAM technologies and adhesive dentistry have improved the application of conservative restorations such as endocrowns and onlays. Among ceramics, zirconia has properties such as high strength, transformation toughening, chemical and structural durability, and biocompatibility, which enable zirconia to be used in the posterior area.

Aim: This study is a comparative evaluation of fracture resistance and failure modes in endodontically treated molars restored with zirconia endocrown and onlays.

Materials and methods: This study was performed on 20 human mandibular first molars with similar dimensions. After root canal treatment, the samples were divided into two groups: endocrowns and onlays (n=10). Restorations were made using a CAD-CAM milling machine with zirconia CAD blocks and, after cementation, subjected to 10,000 thermocycling and 500,000 fatigue cycle procedures, respectively. Each specimen was placed on a Universal Testing Machine and subjected to axial compressive force applied at a crosshead speed of 0.5 mm/min. The mean loads of failure of each group were statistically compared using the Student *t*-test. Chi-square tests were used to compare frequencies of failure modes among groups.

Results: Fracture resistance showed a statistically significant difference between endocrown (5374.6810±670.03445 N) and onlay (3312.5000±804.01428 N) ($p<0.001$). No statistically significant difference was detected in the distribution of failure types among the groups ($p>0.05$).

Conclusions: The fracture resistance of endocrown is substantially higher than that of onlay, and failure type does not differ in both restorations. Zirconia is a reliable material to use in conservative restorations.

Keywords

failure mode, fracture strength, zirconia onlay, zirconia endocrown

INTRODUCTION

Failure in endodontically treated posterior teeth (ETPT) occurs due to reduced fracture strength and stiffness. Increased cuspal deflection during loading and the enlargement of cavity preparation rather than dehydration and physical changes in dentin are the primary reasons.[1-4]

So far, no general agreement has been reached on the best restoration for reconstructing ETPT.[5] Conventionally, such cases were treated using a post and core followed by crown for enhancing the structural integrity and covering the cusps.[6,7] Intraradicular posts have disadvantages such as root perforation and fracture.[3,8,9]

Advances in adhesive dentistry and emphasis on minimally invasive principles for increasing the restoration's longevity led to the development of conservative restorations.[10-12]

When the facial and lingual surfaces of an ETPT are intact, a conservative partial coverage restoration such as onlay can be designed instead of full coverage restoration.[13] Additionally, onlay is known as the minimum treatment of ETPT.[14] They provide a favorable distribution of stress and reduce the risk of tooth and restoration fracture.[15]

On the other hand, as proposed by Pissis in 1995,[1,3,8,16] endocrowns have the post, core and crown assembled in one component. Here, a 'monoblock porcelain technique' was presented.[8,16,17] Bindl and Mörmann first described the term 'endocrown' as adhesive endodontic crowns.[7,17] Endocrowns use the macro retentive support from the pulp chamber walls and the micromechanical retention due to adhesive cementation.[3,8,16,17] Consequently, healthy coronal tooth tissue can be preserved.[3] Moreover, teeth without adequate ferrule effect[3,8], interocclusal space[3,7,8], and short, wide and dilacerated root canals[12] can be reconstructed. Elimination of the laboratory stages can also save time for both the patient and dentist.[3,7,17]

A wide range of materials including feldspathic ceramics, ceramics reinforced with lithium disilicate, zirconia and PEEK have been used in preparing endocrowns and onlays.[18,19] With the development of CAD/CAM technology in dentistry[3], the possibility of milling full contour ceramic restorations without veneering such as zirconia has been enhanced.[20]

Densely sintered Yttria-stabilized tetragonal zirconia polycrystals (Y-TZP) ceramics has mechanical properties such as flexural strength (700-1200 MPa) and fracture resistance (>2000 N) due to its transformation toughening effect. These properties are considerably higher than those of other dental ceramics.[21] Also the wear resistance of both 3Y-TZP and 5Y-TZP was noted as a clinical advantage for patients with bruxism and other destructive habits.[22] Excellent wear properties, biocompatibility, radiopacity, low corrosion potential, volumetric stability, and good chemical properties are the other optimal characteristics noted in the literature.[23]

Although improved mechanical properties are critical for the durability of zirconia restorations, the cementation procedure plays an important role for its clinical success. Conventional methods of adhesive cementation are challenging because of the lack of silica and glass phase in zirconia.[21]

So far, various surface treatments such as airborne-particle abrasion, tribochemical silica coating, selective infiltrative etching and phosphate monomer-containing primers prior to cementation have been suggested.[21,24]

Although some studies have shown higher bond strength of lithium disilicate restorations[25], Kwon displayed similar short- and long-term bond strength of 3- and 5Y-TZP to those of lithium disilicate, by preparing the zirconia surface specimens with airborne particle abrasion.[22]

The effect of the type of material, depth of the pulp chamber, and restoration preparations on the strength of restoration's fracture has been investigated in several studies. Several in-vitro studies showed that the fracture resistance of endocrowns increased with the deeper extension into the pulp chamber.[1,12,26] However, Ghajghouj et al. did not find any correlations between pulp chamber exertions and the fracture resistance values.[26] Some studies have compared the fracture strength of different ceramic restorations. They revealed that the fracture resistance of endocrowns was superior to that of onlays and inlays.[27,28] Moreover, different investigations displayed higher fracture strength of zirconia restorations in comparison to other materials.[10,12,19] To date, few studies have compared the fracture strength of zirconia onlay and endocrown restorations.

AIM

The aim of this study was to compare the fracture strength and failure mode of endodontically treated teeth restored with zirconia endocrown and onlay.

MATERIALS AND METHODS

Twenty human mandibular first molar teeth were selected for this study. Freshly extracted teeth free of anomalies with similar mesiodistal and buccolingual dimensions were measured at the cemento-enamel junction (CEJ) and were included in the study. A maximum deviation of 10% in dimensions was allowed. Internal root resorption, calcified root canals, cracks or fractures were the exclusion criteria. The specimens were ultrasonically cleaned and stored in 0.5% chloramine T disinfectant solution at 4°C for one week.

By using a dental surveyor, each specimen was vertically embedded into autopolymerizing resin (Luxatemp, DGM, Hamburg, Germany) in a cylindrical chamber at 2 mm apical to the cemento-enamel junction to simulate bone level.[2,9,17,20] For standardization, all the specimens were endodontically treated by one operator. After preparing the access cavity, a size of 15 K-file was inserted in the canals for reaching the foramen apical. The working length was 1 mm shorter than the primary length. Root canals were prepared using Protaper Universal (Dentsply Sirona, Johnson city, USA) rotary instruments up to size 50 (F5) following the manufacturer's instructions. The root canals were irrigated with 5 ml of 5.25% NaOCl (sigma-Aldrich, ST. Louis, MO, USA) solution between each instrumentation. Then, 5 ml of 17% EDTA (sigma-Aldrich, ST. Louis, MO, USA) was used with a final rinse with 5 ml distilled water.[3] Canals were dried with paper points (Gapadent Co. Ltd, Tianjin City, China) and then obturated using the cold lateral compaction of gutta percha (Gapadent Co. Ltd, Tianjin City, China) with AH plus sealer (De Trey Dentsply, Konstanz Germany). The excess filling of gutta percha was removed 2 mm under the orifice of each canal. Then, restorative glass ionomer material GC Fuji II LC (GC Corporation, Tokyo, Japan) was used to fill the canals up to the pulp chamber level. The teeth were placed at 37°C with 100% humidity incubator until the preparation.

Specimens were randomly divided into two groups (n=10) according to their restorative preparations: endocrowns and onlays.

Teeth preparation

A 2-mm occlusal reduction of all the specimens was performed with a tapered round-end diamond bur (018, 850 L, Teezkavan, Tehran, Iran). A butt-joint margin with no ferrule was designed.

The retentive form of the pulp chamber for endocrown restorations was achieved by eliminating all the undercuts with a tapered flat-end diamond bur (018, 847). The remaining undercuts were covered with glass ionomer material (GC Corporation, Tokyo, Japan). After a uniform taper of 7° in the pulp chamber was prepared, 4 mm height was standardized with a graduated periodontal probe.[4,7] All the internal line angles became rounded with a polish bur (018, 850).

Before preparing the teeth for onlay restorations, according to the 4.0 mm height of the pulp chamber, 2.0 mm of the chamber was filled with composite resin material (GC Gradia Direct posterior $A_{3,}$ GC Corporation, Tokyo, Japan). The general principles for adhesive onlay restorations were applied.[29] An isthmus width in 2.0 mm followed by 2.0 mm pulpal floor depth was established. Furthermore, a mesial and distal box with a 1.5-mm mesiodistally gingival floor depth and an axial wall height of 2.0 mm was designed. The divergence of approximately 10-12° in the cavity was achieved. All the steps were performed with a tapered round-end diamond bur.

All the internal line angles of the preparations were rounded and a final finishing and polishing with polish bur and mullet (304514, 100, Composhine, Teezkavan, Tehran, Iran) was performed.

Preparation of ceramic restorations

Restorations were fabricated with monolithic zirconia (Superfect Zir HT, Aidite^{R} High technical ceramics Co Ltd, Qinhuangdao, China) blank.

A laboratory scanner (Rainbow™ scanner prime, Dentium, Seoul South Korea) was used for making digital impressions of the teeth preparations. The data was kept as Standard Tessellation Language (STL) file and the restorations were designed. Cement film thickness of 80 μm was selected.[30] The restorations were milled by 5-axis milling machine (Mill-Zir 5-Axis Rainbow™, Dentium, Seoul, South Korea).

Bonding surface treatment and cementation

The restorations were sandblasted (Aeroetcher sandblaster, Parkell INC, NY, USA) using 50 μm Al2O3 air abrasion at 2-bar pressure for 1 minute, and then cleaned in an ultrasonic water bath for 10 minutes.[12]

Enamel surfaces of the teeth were selectively etched with 37% phosphoric acid (Morva Etch, Morva Bon, Iran, Dentaj. IR) for 20 seconds followed by water rinse and air drying. Primer A and primer B (Ivoclar Vivadent AG, Schaan/Liechtenstein) were mixed with the equal ratio of 1:1 and gently applied on the teeth within 30 seconds.

After painting mono-component silane (Mono Bond N, Ivoclar Vivadent AG, Schaan/Liechtenstein) on the intaglio surface of the restorations within 60 seconds, the dual cure resin cement Multilink N (Ivoclar Vivadent AG, Schaan/Liechtenstein) was applied and seated on each tooth with finger pressure. The excess cement was removed after 4 seconds tack light curing by a scaler. Each surface was light cured (Woodpecker, DTE ®LUX E, Guilin China) definitively at 1200 mw/cm^2 intensity for 40 seconds. The specimens were stored in a humid environment at 37°C for 72 hours to finalize the polymerization.

Aging procedure and fracture test

All specimens were thermocycled (SD mechatronic thermo cycler, Feldkirchen, Germany) for 10000 times between 5°C and 55°C with a dwell time of 30 seconds in each bath. The transfer time was 10 seconds. In addition, 500,000 cyclic loads (chewing simulator CS-4, SD Mechatronic, GmbH, Germany) were performed with a stainless steel ball (diameter of 4 mm). The magnitude of the force was 100 N, which was applied on the center of the occlusal surface at the frequency of 4 Hz and 0.6 mm cut off. The specimens were subjected to a universal testing machine (Zwick / Roell Z050, ULM, Germany) after no cracks or fractures was observed under the stereomicroscope. An axial compressive load was performed vertically on the centric fossa of the restorations by a metal sphere of 6 mm in diameter. The cross-head speed of 0.5 mm/min and 50 kN load cell was applied until the failure happened.

Failure modes

Fractured specimens were observed under a stereomicroscope (Nikon SMZ 1500, Tokyo, Japan) at magnifications

10× by one operator and the failure types were classified as follows:

Type 1: adhesive failure between restoration and teeth
Type 2: cohesive failure within the restoration
Type 3: mixed type failure above the CEJ
Type 4: mixed type failure below the CEJ

Fractures above the CEJ could be repairable, while fractures below the CEJ and extending to the root are considered irreparable.[31]

Statistical analysis

Fracture strength of the specimens was analyzed using the Student *t*-test. Evaluation of failure types was performed using chi-square test. The analysis was done using Statistical Package for Social Sciences (SPSS), version # 21(SPSS Inc.IL, USA). The level of significance was 0.05.

Ethical considerations

The study was approved by the research ethics committee of Qazvin University of Medical Science (IR.QUMS.REC.1398.157).

RESULTS

The mean fracture strength (load at fracture in Newton) for the two tested groups were as follows: endocrowns: 5374.6810±670.03445 N and onlays: 3312.5000 N (**Table 1, Fig. 1**).

According to the frequency of the failure modes, in the endocrown group, 10% type 1, 10% type 2 and 80% type 4 failure mode were detected. Furthermore, in the onlay group, 10% type 2 and 90% type 4 failure mode were observed (**Table 2, Fig. 2**). One sample of each failure type is shown as stereomicroscopic image in **Figs 3-6.**

DISCUSSION

There is no consensus regarding the most successful treatment procedure in restoration of endodontically treated posterior teeth (ETPT). It seems that the higher amount of preserved coronal tooth structure has a significant effect on the long-term survival of these teeth.[28]

Conservative restorations such as onlays and endocrowns allow a minimal tooth structure removal which can preserve and strengthen the remaining dental tissues.[16] By avoiding the ferrule effect, which is critical for conventional crown preparation, more sound enamel or dentin surface is

Table 2. Percentage of the failure modes of the test groups

Failure mode	Endocrown	Onlay	*P* value
I	1 (10)	0	0.065
II	1 (10)	1 (10)	
III	0	0	
IV	8 (80)	9 (90)	

Type I: adhesive failure; Type II: cohesive failure; Type III: fracture of the restoration/tooth complex above the CEJ; Type IV: fracture of the restoration/tooth complex below the CEJ

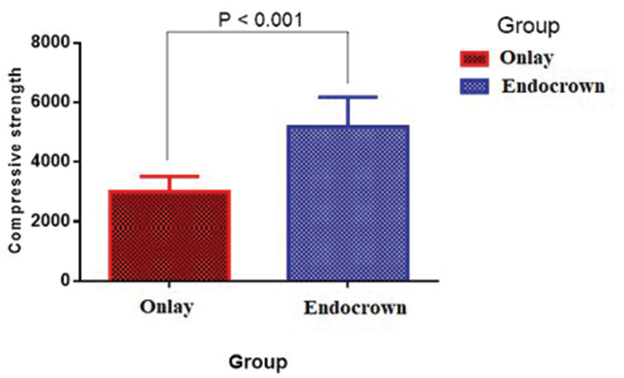

Figure 1. Compressive strength (N) of endocrown and onlay restorations.

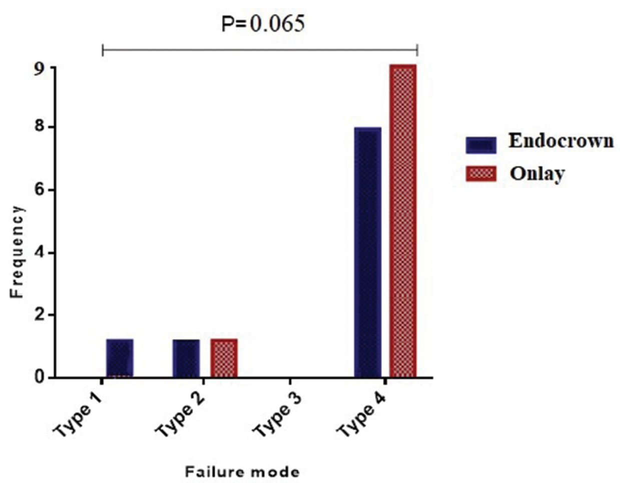

Figure 2. Percentage of failure modes in endocrown and onlay restorations.

Table 1. Distribution of compressive fracture strength (N) by endocrown and onlay restorations

	Mean	SD	Minimum	Maximum	*p*
Endocrown	5374.6810	670.03445	4428.82	6870.30	<0.001
Onlay	3312.5000	804.01428	2149.87	4998.71	

Figure 3. Stereomicroscopic image ×10 presenting type II (cohesive failure within the restoration) failure mode of onlay specimen.

Figure 6. Stereomicroscopic image ×10 presenting type (mixed type failure below the CEJ) failure mode of onlay specimen.

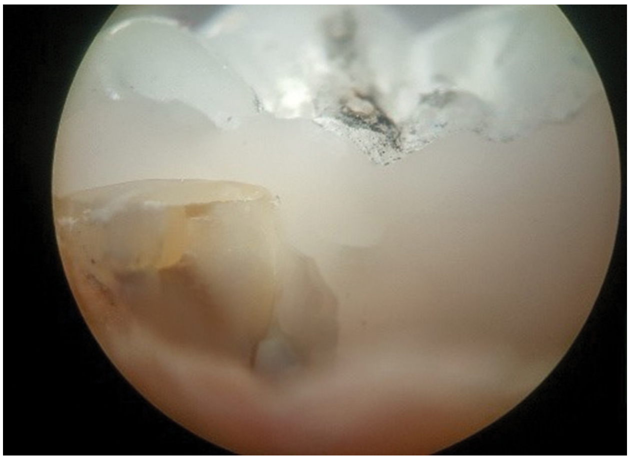

Figure 4. Stereomicroscopic image ×10 presenting type (cohesive failure within the restoration) failure mode of endocrown specimen.

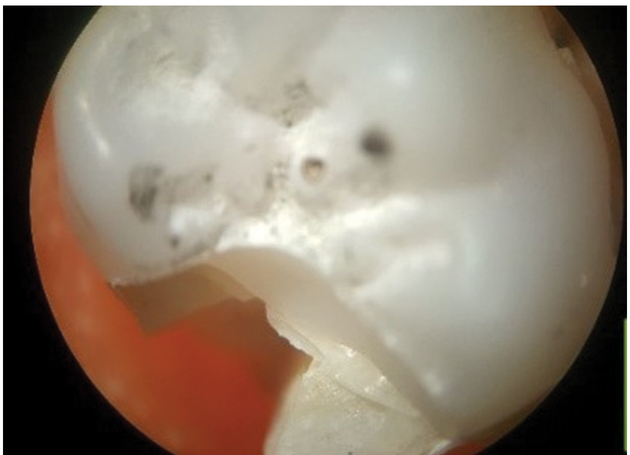

Figure 5. Stereomicroscopic image ×10 presenting type (mixed type failure below the CEJ) failure mode of endocrown specimen.

left for the bonding process to the restoration.[16,32]

A monolithic zirconia restoration is stronger than the bi-layered one. Thus, they may be used for restoring teeth without removing an excessive amount of sound tooth structure.[33] It has been proven that zirconia is suitable for stress bearing applications, such as long span fixed partial prostheses[34] and patients with high masticatory forces due to bruxism or other parafunctions.[15] However, there is scarcity of information regarding their application in conservative treatment concepts.[34]

The mandibular molar teeth were used in this study as they are the best teeth for receiving endocrown restorations.[4,7,9]

In several studies, thermocycling was combined with cyclic loading to represent an artificial aging.[9,10,19] In the current study, the specimens were first thermocycled 10000 times which resembles one year of in-vivo use.[35] As the number of chewing cycles per day is approximately estimated to be 800-1400, a moderate 500,000 cycles were applied for functioning the restored teeth per year.[36,37]

After the aging procedure, all of the specimens were examined under a stereomicroscope and no fracture or cracks were detected. Wang et al.[37] demonstrated that zirconia was unresponsive to the same number of cyclic loads from a macroscopic point of view. Cyclic loading with an increased number of cycles has been shown to propagate fractures and decrease the strength of zirconia restorations in the previous studies.[38] There are different parameters with regards to the duration and frequency of loading as well as the size and load of the indenter in different studies. Therefore, evaluating and comparing the real effects is still challenging.

The mean fracture strength was 5374.6810±670.03445 N in endocrowns and 3312.5000±804.01428 N in onlay restorations, which both were in a higher range in comparison with other studies. The mean fracture strength range obtained from zirconia onlay and endocrown restorations in different studies was 1011.73-2568.76 N[16,20,39] and 1588.33-3533 N[12,19] respectively. Several aspects can be involved in the results obtained in this study, which are mentioned in order.

The type of zirconia material and the aging procedures, which are used in studies, are responsible for the different results. A presintered monolithic zirconia with 95% crystallization (Superfect Zir, Aidite^R, High technical ceramics Co, Ltd, Qinhuangdao, China) with 10000 thermocycling procedure and 500,000 cyclic loads were used in this study. Elashmawy et al.[19] reported the mean fracture strength of 1588.30 N in monolithic zirconia (KATANA, Kuraray, Noritake, Japan) (with 89.92% crystallization) endocrown after applying 15000 thermocycling and 600,000 cyclic loads. On the other side, Dartora et al.[10] revealed a mean fracture strength of 6333 N of the monolithic zirconia (Zirk OM SI, Aidite^R, High technical ceramics Co Ltd, Qinhuangdao, China))with 94.39% crystallization) endocrown after 20000 cyclic loading process. The higher degree of crystallization and number of thermocycling procedures may explain this difference.

Different preparation design and pulp chamber extension are the other critical factors.

The fracture strength of endocrown restorations was significantly higher than the strength of onlay restorations (p<0.001). This may be explained by the main difference between the groups, which was the depth of pulp chamber. The pulp chamber extension of endocrowns and onlays were 4 mm and 2 mm, respectively. In some previous studies,[1,26] it has been revealed that the fracture strength of the endocrown restorations was enhanced with the greater pulp chamber depth. Also, Haralur et al.[12] displayed a higher fracture strength of zirconia endocrown restorations with a 5-mm pulp depth than the 3-mm ones. On the other hand, Ghajghouj et al. did not show any differences between the endocrowns with different pulp extensions.[26]

The result of the present study, which revealed higher fracture resistance in endocrown restorations, is in agreement with the results of some previous studies evaluating restorations made of different materials. Hamdy et al. reported higher fracture resistance of lithium disilicate endocrowns than the resistance of onlays and inlays.[28]

Similar observation of greater fracture resistance of hybrid ceramic endocrowns in comparison with onlays and inlays was also reported by Kassis et al.[27] According to the 3D finite element analysis by Prina et al., endocrown restorations showed a better stress distribution in enamel and dentin than onlay restorations when a force of 200 N, 500 N, and 800 N was applied.[39] This result may be due to the fact that endocrowns show advantages such as reducing the effect of multiple interfaces of the restorative system or offering a greater ceramic thickness withstanding the compression forces. The same result was also achieved by Durand et al.[40], who reported that models only restored by ceramic material and bonded directly into the cavity showed better stress distribution than models restored with composite bases.

In this study, the monolithic zirconia restorations were luted with Multilink N, which is a dual cure self-adhesive resin cement. Besides the simplicity of cementation procedure of a self-adhesive cement, the self-cure mode ensures optimal polymerization and the phosphate monomers may guarantee a durable bonding both to enamel and dentin and to zirconia surface.[41,42]

The surface pretreatment protocol used for zirconia restorations in this study involved sandblasting, which has reported to be the most effective according to some previous studies.[21,43] Bond strength to zirconia is improved by airborne particle abrasion which roughens and increases the surface area. Also, chemical bonding between phosphate monomers and zirconia takes place after generation of hydroxyl groups on the surface.[21,44]

Stereomicroscopic analyses revealed the majority of type 4 failure mode under compressive loading in both groups, which was irreparable. None of the specimens showed type 3 failure mode. Both groups showed type 2 failure mode and type 1 was only detected in the endocrown group. In line with the current study, some previous studies[10,19] reported most type 4 failure modes in the zirconia endocrown restorations. It has been shown that the elastic modulus affects the susceptibility of fracture resistance. Since materials with more compatible elastic modulus to the teeth distribute stresses more evenly, while more rigid materials such as zirconia concentrates the stress at critical areas and cause catastrophic failures.[45] Also, Zarone et al.[46] found that a greater difference between elastic modulus of resin cement, material of restoration and teeth structure may lead to a higher catastrophic failure which extends to the root.

In another study, Saridag et al.[47] displayed a majority of type 4 failure mode in zirconia onlay restorations in comparison with the inlay and lithium disilicate restorations.

The results of this study are in contrast with the results reported by Erturk et al.[3], who found that in monolithic zirconia endocrowns only 10% of the specimens in 3 mm and 40% in 6 mm depth of pulp chamber showed type 4 failure mode. It can be explained by the selection of maxillary incisor teeth, different design of endocrown restoration, and a 45° applied loading force.

Harsha et al.[20] revealed only 30% type 5 failure mode (fracture in the restoration and the tooth below CEJ) and 70% type 1 failure mode (no visible fracture in the restoration and tooth) in maxillary premolars reconstructed with zirconia onlay restorations. Different tooth selection and preparation design, less cuspal reduction and designing a ferrule on both buccal and palatal cusp may account for this difference.

This study had a number of limitations. Thermocycling and static chewing simulator was used to simulate the conditions of oral environment, but it was limited to 10000 and 500000 cycles. Due to the high fracture strength of the zirconia restorations in the present study, more studies are needed to evaluate the effect of long-term fatigue test on this material. Also, involving artificial saliva with dynamic cyclic loading and non-axial loading directions are proposed for the further studies.

CONCLUSIONS

Compressive fracture strength of endodontically treated molar teeth reconstructed with zirconia endocrown restoration is higher than that of onlay restorations and the failure type mode was not seen to be different between the zirconia endocrown and onlay restoration.

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Сравнительная оценка сопротивления переломам и видов разрушения эндодонтически леченных моляров, восстановленных с помощью циркониевых эндокоронок и накладок

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Резюме

Введение: Развитие стоматологических материалов, технологий CAD/CAM и адгезивной стоматологии улучшило применение консервативных реставраций, таких как эндокоронки и накладки. Среди керамики цирконий обладает такими свойствами, как высокая прочность, трансформационная стойкость, химическая и структурная стойкость, а также биосовместимость, что позволяет использовать диоксид циркония в области боковых зубов.

Цель: Это исследование представляет собой сравнительную оценку устойчивости к переломам и видов разрушения эндодонтически пролеченных моляров, восстановленных с помощью эндокоронок и накладок из диоксида циркония.

Материалы и методы: Это исследование было выполнено на 20 первых молярах нижней челюсти человека с аналогичными размерами. После обработки корневых каналов образцы были разделены на две группы: эндокоронки и накладки (n=10). Реставрации были изготовлены с использованием фрезерного станка CAD-CAM с блоками CAD из диоксида циркония и после цементирования подверглись 10 000 процедур термоциклирования и 500 000 циклов усталости соответственно. Каждый образец помещали в универсальную испытательную машину и подвергали осевому сжатию со скоростью траверсы 0.5 mm/min. Средние нагрузки отказа каждой группы статистически сравнивались с использованием t-критерия Стьюдента. Тесты хи-квадрат использовались для сравнения частот режимов отказа среди групп.

Результаты: Сопротивление перелому показало статистически значимую разницу между эндокоронкой (5374.6810±670.03445 N) и накладкой (3312.5000±804.01428 N) ($p>0.001$). Статистически значимой разницы в распределении типов отказов между группами выявлено не было ($p<0.05$).

Заключение: Прочность на сжатие эндокоронки значительно выше, чем у накладки, а тип разрушения у обеих реставраций не отличается. Цирконий — надёжный материал для консервативных реставраций.

Ключевые слова

вид разрушения, прочность на излом, накладка из диоксида циркония, эндокоронка из диоксида циркония