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Original Research Article

The Effects of Different Beverages on Fracture Resistance of CAD/CAM Monolithic PEEK and Monolithic Zirconia Crowns

Farklı İçeceklerin CAD/CAM Monolitik PEEK ve Zirkonya Kronların Kırılma Dayanımlarına Etkisi

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ABSTRACT

Aim: To assess the impact of various beverages on the fracture resistance of CAD/CAM polyetheretherketone (PEEK) and monolithic zirconia materials.

Materials and Method: We fabricated eighty CAD/CAM materials from PEEK polymer (CopraPeek; Whitepeaks Dental Solutions GmbH, Germany) and monolithic zirconia (inCoris TZI; Dentsply Sirona Systems GmbH, Bensheim, Germany), with ten samples per group. These samples were submerged in either distilled water, cola, coffee, or red wine and stored at 37°C for 12 days. We utilized a universal testing machine (Lloyd LRX; Lloyd Instruments Ltd., West Sussex, UK) to measure each sample's fracture resistance. The t-test provided a comparison of normally distributed variables between the two groups. For multiple group comparisons, we executed an analysis of variance (ANOVA).

Results: A statistically significant difference was observed between the PEEK and zirconia groups in terms of maximum load and elastic load-bearing capacity values ($p<0.05$), with zirconia materials yielding higher values. However, there was no critical difference in these measures obtained from different solutions for neither PEEK nor zirconia samples ($p>0.05$).

Conclusion: CAD/CAM monolithic PEEK material stored in various solutions demonstrated lower fracture resistance and elastic strength than monolithic zirconia materials. Despite this, PEEK exhibited the highest fracture resistance to intraoral occlusal forces. Accordingly, due to its chemically inert nature and superior force absorption, we recommend PEEK as a viable alternative material for posterior crowns in fixed restorations.

Keywords: Dental CAD/CAM; Fracture Strength; Monolithic zirconia; PEEK

ÖZET

Amaç: Bu çalışmanın amacı; farklı içeceklerin CAD/CAM polietereterketon (PEEK) ve monolitik zirkonya malzemelerinin kırılma direnci üzerindeki etkilerini değerlendirmektir.

Gereç ve Yöntem: PEEK ve monolitik zirkonyadan her grupta 10 örnek olmak üzere toplam 80 CAD/CAM malzemesi üretildi. Örnekler 12 gün boyunca 37°C'de distile su, kola, kahve ve kırmızı şarapta saklandı. Her numunenin kırılma direncini belirlemek için üniversal test cihazı kullanıldı.

Bulgular: PEEK ve zirkonya grupları arasında maksimum yük ve elastik yük taşıma kapasitesi değerlerinde istatistiksel olarak anlamlı fark tespit edildi ($p<0.05$). Zirkonyum malzemeler en yüksek kırılma direnci sergilerken hem PEEK hem de zirkonya örneklerinin farklı içeceklere maruz bırakılması neticesinde maksimum yük ve elastik yük taşıma kapasitelerinde istatistiksel olarak anlamlı bir fark tespit edilmedi ($p>0.05$).

Sonuç: Farklı solüsyonlarda bekletilen CAD/CAM PEEK malzemesi, monolitik zirkonyaya göre daha düşük kırılma direncine ve elastik mukavemete sahipti. Ancak, PEEK dental materyallerinin kimyasal olarak inert yapısı ve yüksek absorpsiyon kapasitesi nedeniyle yine de posterior bölgenin sabit restorasyonu için alternatif bir kron materyali olarak kullanılabileceğini öneriyoruz.

Anahtar Kelimeler: Dental CAD/CAM; PEEK; Monolitik zirkonya; Kırılma direnci

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INTRODUCTION

While the biological and functional properties of materials used in posterior restorations are essential in dentistry, aesthetic outcomes take precedence in anterior restorations. The choice of restoration material depends greatly on the location and extent of tooth tissue loss. Thanks to advancements in technology, computer-aided design/computer-aided manufacturing (CAD/CAM) restorations have gained popularity due to their proven durability. These are frequently used in inlays, onlays, laminate veneers, and all-ceramic crown restorations.[1]

Dentists often use metal-supported fixed restorations for rear teeth due to their affordability and durability. Nonetheless, with the latest digital innovations, the spectrum of dental materials has broadened, facilitating more robust, aesthetic, and fast restorations. The use of all-ceramic and other materials is becoming increasingly common in restorations. Nowadays, dentists can create dental restorations with superior aesthetics, biocompatibility, and mechanical strength compared to traditional methods, bypassing the need for labs.[2,3]

While all-ceramic restorations present excellent aesthetic and mechanical results in standard aesthetic dentistry applications, their use in posterior restorations is limited due to low fracture resistance. Monolithic zirconia, characterized by high fracture resistance, considerable elastic modulus, and fracture toughness of up to 2000 MPa, is commonly used in posterior aesthetic restorations.[4] However, zirconia has its downsides: it tends to degrade at low temperatures and the superstructure may chip during function, caused by the thermal expansion coefficient disparity between zirconia and the superstructure.[2,4] Consequently, the use of monolithic zirconia in posterior restorations has become more prevalent. Despite their robustness, zirconia-based materials may weaken over time due to fatigue and accumulated microcracks, reducing their durability under functional forces.[5]

Polyetheretherketone (PEEK) is a high-performance polymer frequently used in clinical dentistry due to its exceptional characteristics. These include low water and moisture absorption (0.5 g/mm^3), high resistance to chemical agents and temperature changes, and enhanced patient comfort due to its lightweight nature.[6-8] PEEK is also highly biocompatible—its semi-crystalline structure is less brittle than that of zirconia oxide. It boasts tensile strength similar to enamel and dentin and has demonstrated no cytotoxic, mutagenic, or carcinogenic effects. Additionally, PEEK can absorb occlusal forces. Furthermore, PEEK is well-suited for fixed prosthetic restorations because of its unique properties like lower failure rates and ease of shaping and polishing.[8,10] However, it does have shortcomings. Its grayish color and high opacity are unsuitable for aesthetic restorations when used solely. To counter this, composite resins are applied for veneering. Since PEEK's inert chemical structure is highly resistant to surface alterations, connection issues with the superstructure may arise. As such, PEEK is recommended for posterior fixed restorations where aesthetics are not a focal point.[11,12] It can also offer a reliable solution for patients with bruxism or parafunctional habits, as it does not cause wear on opposing teeth and can absorb excess stress.[13] Though there is limited literature about fixed prosthetic restorations using CAD/CAM PEEK materials, its practical use is growing.[11]

The hardness of restoration surfaces can be degraded due to external factors such as colorants in food and drinks, dietary habits, oral hygiene products, and cigarettes, possibly leading to wear or damage to the material's surface structures.[14] This *in vitro* study hypothesized that monolithic CAD/CAM PEEK and zirconia materials would exhibit comparable fracture resistance against various beverages. The study's purpose was, thus, to examine the impact of different beverages on the fracture resistance of these materials.

MATERIALS AND METHOD

We prepared samples from PEEK discs and monolithic zirconia blocks with a precision cutting machine (Mod-Dental, Esetron, Ankara, Turkey). From semi-sintered zirconia blocks (inCoris TZI; Dentsply Sirona Systems GmbH, Bensheim, Germany), we obtained 15×12×2 mm sections. These sections are suitable for monolithic use. We accounted for a possible 20% reduction during the sintering process.

Before sintering, we dried the samples in a porcelain oven (Programat P300; Ivoclar Vivadent AG, Liechtenstein, Germany) at 80°C for 30 min. We used a porcelain furnace (inFire HTC, Dentsply Sirona Systems GmbH, Bensheim, Germany) to sinter the dried samples as per the manufacturer's instructions. We heated them from 25°C up to 1,510°C over a period of 2 h.

During the sintering process, the samples shrank by 20% to 12 × 10 × 1.5 mm. We produced a total of 40 samples. We used a digital calliper (Alpha Tools GmbH, Mannheim, Germany) to determine the thickness of the samples from three different regions.

Additionally, we made 40 more samples of the same size from a 95 × 15 mm PEEK disc (CopraPeek; Whitepeaks Dental Solutions GmbH, Germany) using the precise cutting machine. We measured the thickness of these samples, as before, at three separate points with a digital calliper.

Finally, we divided both the PEEK and monolithic zirconia samples into four equal groups, each containing differing solutions for the fracture test. Each group held ten of both the PEEK and monolithic zirconia samples.

Group 1: Distilled water
Group 2: Cola (Coca-Cola İçecek A.Ş., Istanbul, Turkey)
Group 3: Red wine (Kayıbağ Şarapçılık, Denizli, Turkey)
Group 4: Coffee (Blend #37; Nestle Türkiye Gıda Sanayi A.Ş., Istanbul, Turkey). In accordance with the manufacturer's recommendation, 2 g of coffee was added to 200 mL of hot water, mixed, and kept until room temperature.
Ten sample groups were stored in 50 mL Falcon tubes, each with 20 mL of solution. Typical daily beverage consumption was estimated at 3.2 cups, each lasting 15 min, with a 12-day waiting period interspersed throughout a 1-year period.[16] To simulate this annual consumption pattern, the samples were kept in the solutions for 12 days with the same consumption rate.

For experimental purposes and to imitate the oral environment, the samples were stored in an oven (Edwards Vacuum, Crawley, UK) at 37°C for 12 days. The solutions were refreshed every two days and mixed daily to prevent sediment deposit accumulation. Subsequently, the samples were tested using a universal testing machine (Lloyd LRX; Lloyd Instruments Ltd., West Sussex, UK) at 1 mm/min. All samples underwent three-point loading tests, which were repeated until breakage occurred.

Statistical analysis

We conducted all statistical analyses using IBM SPSS software version 22.0. Descriptive data is presented as either mean ± standard deviation (SD) or as a number and frequency, where needed. The Shapiro-Wilk test indicated a mix of normal and non-normal data distribution across different groups. To compare non-normally distributed variables between the two groups, we employed the Mann-Whitney U test, while the Kruskal-Wallis H test was used for multiple group comparisons. The t-test was used to compare normally distributed variables between two groups, with the analysis of variance (ANOVA) applied for multiple groups. Finally, we used the Pearson correlation coefficient to identify potential correlations between variables.

RESULTS

There was no statistically significant difference both maximum loading values and the elastic strength values of the zirconia material in different solutions ($p>0.05$) (Tables 1 and 3). Likewise, there was no significant difference these values of the PEEK material in different solutions ($p>0.05$) (Table 2 and 4). In the meantime, the results indicated that monolithic zirconia demonstrated maximum fracture strength in distilled water and elastic strength in red wine. It was observed that the PEEK material had the optimal fracture and elastic strength when in cola.

Significant differences were observed in the maximum load values (measured in Newtons) between PEEK and zirconia samples, with zirconia showing higher values ($p<0.05$) (Table 5). Zirconia samples also showed higher elastic strength (measured in MPa) compared to the PEEK samples ($p<0.05$) (Table 6).

The Spearman correlation test demonstrated a significant and positive correlation between the maximum load (N) and elastic strength (MPa) values ($r=0.955$; $p<0.05$). Thus, an increase in maximum load (N) corresponds to an increase in elastic strength (MPa).

Table 1. Maximum loading values of zirconia (Newton)

Maximum loading (N)	Zirconia				ANOVA test
	n	Mean±SD	Min	Max	P
Distilled water	10	1238.6±275.3	752.9	1785.4	0.77
Cola	10	1184.7±240.0	830.2	1609.5	
Coffee	10	1127.2±171.8	884.1	1324.9	
Red wine	10	1200.6±256.1	706.9	1513.5	

SD: standard deviation
*No significant difference between the test groups (p>0.05).

Table 2. Maximum loading values of PEEK (Newton)

Maximum loading (N)	PEEK					Kruskal- Wallis H test
	n	Mean±SD	Min	Max	Rank average	P
Distilled water	10	499.5±59.3	409.3	613.9	15.3	0.09
Cola	10	808.6±478.2	474.6	1743.9	27.3	
Coffee	10	502.6±69.9	400.1	604.4	17.3	
Red wine	10	536.5±41.5	468.6	606.0	22.1	

SD: standard deviation
*No significant difference between the test groups (p>0.05).

Table 3. Elastic strength values of zirconia (MPa)

Elastic strength (MPa)	Zirconia					Kruskal-Wallis H test
	n	Mean±SD	Min	Max	Rank average	P
Distilled water	10	878.7±217.3	619.8	217.3	14.5	0.23
Cola	10	965.1±185.4	688.6	185.4	20.7	
Coffee	10	892.8±195.1	539.1	195.1	17.2	
Red wine	10	1020.4±202.9	640.2	202.9	24.5	

SD: standard deviation
*No significant difference between the test groups (p>0.05).

Table 4. Elastic strength values of PEEK (MPa)

Elastic strength (MPa)	PEEK					Kruskal-Wallis H test
	n	Mean±SD	Min	Max	Rank average	P
Distilled water	10	277.7±32.4	233.7	314.9	16.4	0.17
Cola	10	557.8±457.7	272.7	1434.6	23.4	
Coffee	10	276.6±44.5	216.9	335.1	16.5	
Red wine	10	316.6±35.2	270.1	379.0	25.7	

SD: standard deviation
*No significant difference between the test groups (p>0.05).

Table 5. Maximum loading values of the materials (Newton)

Maximum loading (N)						Mann-Whitney U test
	n	Mean±SD	Min	Max	Rank average	P
Zirconia	40	1187.8±233.2	706.9	1785.4	58.4	0.00
PEEK	40	586.8±268.6	400.1	1743.9	22.7	

SD: standard deviation
*There is significant difference between these groups (p<0.05).

Table 6. Elastic strength values of the materials (MPa)

Elastic strength (MPa)						**Mann-Whitney U test**
	n	Mean±SD	Min	Max	Rank average	P
Zirconia	40	936.1±56.7	539.1	1438.9	56.8	0.00
PEEK	40	357.2±22.6	216.9	1434.6	22.6	

SD: standard deviation

* There is significant difference between these groups ($p<0.05$).

DISCUSSION

This *in vitro* study examined how various beverages impacted the fracture resistance and elastic strength of monolithic CAD/CAM PEEK and zirconia. The findings showed significant variations in the fracture resistance and elastic strength of dental materials, with monolithic zirconia performing better.

Dental restoration materials used in prosthetic treatments may lose durability due to thermal stresses. These stresses are frequently caused by the consumption of hot and cold food and beverages. Over time, these factors can result in stress on the restoration materials, leading to the growth of microcracks. Furthermore, food and beverages can degrade dental materials by dissolving their monomeric components. These reactions might diminish material hardness, increase surface roughness, and expedite teeth wear.[17]

Immersing dental materials in colouring liquids is a straightforward procedure, but it is crucial to note that these materials can absorb heat, moisture, pH, alcohol, or dye-containing liquids. Such absorption can negatively affect the mechanical resistance of the dental materials.

According to a study by Sulaiman *et al.*[18], the maximum restoration thickness for monolithic zirconia should be 1.65 mm to ensure light transmission, cement polymerization, and durability. In a similar vein, we prepared our study samples to a thickness of 1.5 mm.

Durability is a primary concern when selecting materials for fixed restorations in the posterior region, which are subject to heightened occlusal forces. Monolithic zirconia offers enhanced mechanical resilience and higher survival rates than many other dental materials. In addition, it offers more aesthetic results compared to metal-supported restorations. Thus, it has become a popular choice for fixed restorations in the posterior region.[19,20] Recent research indicates that PEEK could be a viable alternative for these restorations, as it boasts high flexibility, minimal wear, and a superior ability to absorb occlusal stress.[12,21]

The moist conditions found in the oral cavity generally accelerate the development of subcritical cracks in ceramic structures, prompting an unpredictable shift from tetragonal to monoclinic structures of Y-TZP. Consequently, this affects the durability of zirconia restorations.[5] The growth of these subcritical cracks comes from the interaction of water molecules with the ionic-covalent bonds within the cracks.

Additionally, water molecules can integrate into zirconia's lattice structure. This reduces the energy barrier and accelerates the conversion from tetragonal to monoclinic, which in turn speeds up the conversion rate. The subsequent increase in volume contributes to the formation of microcracks in the lattice. Despite this process typically being slow at body temperature, it can still undermine the strength of dental restorations.[5,22]

In this study, we attributed the reduction in the elastic strength of monolithic zirconia material kept in distilled water to the inclusion of water molecules in the zirconia structure. In a separate study, it was noted that the level of the Y203 stabilizer (yttrium oxide) in zirconia materials kept in a neutral solution decreased over time. This indicated that Y-TZP could become more vulnerable to degradation even in environments less humid and corrosive than average.[23] The study's authors also reported that environmental impacts weakened the surfaces of zirconia materials, making them prone to corrosion.

Several studies have highlighted the negative impact of acidic solutions on the crystal structure and mechanical properties of Y-TZP.[24,25] The degree of these effects, however, varies based on both the specific acidic solution used and the surrounding temperature. One particular study found that when Y-TZP restorations were kept in acetic and citric acid at room temperature, attributes like elastic resistance, surface quality, and Vickers hardness remained unaltered.[25] A different investigation into the fracture and elasticity of CAD/CAM dental materials stored in various liquids, including cola, white wine, orange juice, artificial saliva, and gastric juice at 37°C, showed the zirconia material had the highest initial elastic strength. This strength, however, diminished over time with cyclic fatigue.[26] Our study supported these findings, revealing that monolithic zirconia kept in acidic beverages such as red wine and cola had significantly greater elastic resistance when compared to other solutions. This enhanced elastic resistance of monolithic zirconia may be due to the temperature of the storage environment.

The study revealed that cola, which is a highly acidic drink, caused less colour variation in resin-based materials (such as Vita Enamic® and PEEK) compared to coffee.[13] The researchers concluded that the high polarity of cola resulted in decreased absorption and limited adhesion to the surface, which could potentially aid in its removal from the material surface when rinsed. Similarly, our study indicated that cola showed the highest values for load capacity and tensile strength, likely because PEEK material is chemically non-reactive, and its high polarity prevents cola from being absorbed.

Bite force varies significantly, ranging from 585 to 967 N, influenced by factors like age, craniofacial morphology, and occlusal aspects.[10] It is crucial to select materials resistant to these chewing forces. While a sizable difference exists between monolithic zirconia and PEEK material, PEEK exhibits ample structure to withstand the expected bite forces within the mouth.[27] Elashmawy *et al*.[27] illustrated that an increase in a dental material's elastic modulus leads to a marked rise in fracture resistance. A six-month study *in vivo* demonstrated that CAD/CAM PEEK crowns in the posterior region could serve as an alternative to metal crowns, offering higher resistance to occlusal forces.[12] However, zirconia is more prone to high-stress concentrations in pivotal areas, leading to irreversible, catastrophic failures.[27] Such failures are less likely with PEEK materials, which can be repaired if fractured. When a material's elastic modulus is closer to that of human dentin, the force transmitted directly to the tooth and tissues would be reduced, preventing fractures caused by overload.[27] PEEK material has a considerably lower elastic modulus than zirconia, making it suitable for crowning severely damaged teeth in crucial zones.

Atsü *et al*.[28] examined the fracture resistance of various dental materials in a lab setting. They suggested that ceramic-reinforced PEEK abutments may serve as an alternative to zirconia abutments for anterior region restorations. This is due to their optimal fracture patterns and maximum anterior bite forces, which might be because zirconia is more thermocycling and material phase change sensitive. They also found that the elasticity of ceramic-reinforced PEEK was similar to a natural tooth and more flexible than its crown, leading to easier repair in case of failures.

In another study, Liebermann *et al*.[29] assessed the impact of different aging treatments on various CAD/CAM polymers. They stored the samples in sodium chloride, artificial and physiological saliva, and distilled water at 37°C for 180 days. The results showed that PEEK had the lowest water absorption and solubility. The authors concluded that the more uniform the polymer, the less water it absorbed and the less soluble it was.

Despite PEEK's resistance to solutions in our study, Liebermann *et al*.[29] noted significant changes in the physical and mechanical properties within the first 30 days of testing. The divergence between our findings and those of Liebermann *et al*. might be due to the shorter testing duration in our study.

In a study by Prechtel *et al*.[30], extracted human maxillary and mandibular molars were used to create samples from unfilled PEEK materials through additive and fused layer manufacturing. The authors found that all indirect inlays during a simulated chewing experiment displayed a higher fracture load than the forces encountered during normal chewing. This was attributed to the lower Young's modulus of PEEK compared to that of dentin and enamel.

Our study also uses unfilled PEEK material, yielding a higher fracture resistance than the forces present in the oral cavity, despite differences in study design. An *in vivo* study compared PEEK and zirconia inlay restorations in the posterior region, concluding that PEEK could serve as an alternative to zirconia. However, these authors utilized BioHPP, a biocompatible high-performance polymer enhanced by adding a 20% ceramic filler.[1] Weemployed unfilled PEEK material in our study to evaluate the impact of beverage solutions on the fracture resistance of the chemically inert PEEK in comparison to zirconia.

Tartuk *et al*.[7] conducted an *in vitro* study to assess the load-bearing abilities of monolithic PEEK, zirconia, and hybrid ceramic molar crowns. Their findings indicated no significant difference in the performance of PEEK and hybrid ceramic molar crowns. However, zirconia crowns demonstrated the highest fracture load values. The authors inferred that all three materials performed successfully. Additionally, they noted PEEK's effectiveness in withstanding physiological occlusal forces, suggesting its suitability for fixed prostheses in the posterior region.

Different from our study, the previous research used a CAD/CAM monolithic crown with an occlusal thickness of 2mm and an axial thickness of 1.55 mm. Although the impact of post-cementation immersed in solutions remains unclear, the findings were remarkably similar.

Monolithic zirconia has a lower elastic modulus compared to dental tissue, and it does not accurately reflect the strength between an *in vitro* crown and a zirconia crown cemented on a tooth in the mouth. The fracture resistance of the fixed restoration increases as the elasticity modulus of the abutment increases. Forces applied to the cemented restorations are partially absorbed by the cement. In this study, the impact of cement absence on the load-bearing capacity of PEEK and zirconia crowns could not be evaluated. Similarly, this research did not explore the effects of extra aging processes caused by chewing simulation and thermal cycling on these materials. To fully grasp these effects on monolithic CAD/CAM PEEK and zirconia, further *in vivo* and *in vitro* studies are needed.

CONCLUSION

In conclusion, our study indicates that when stored in various solutions, the fracture resistance and elastic strength of CAD/CAM monolithic PEEK material are lower than those of monolithic zirconia. However, PEEK material demonstrates superior fracture resistance against intraoral occlusal forces. Given these results, we propose that PEEK dental materials, with their chemically inert structure and high absorption capacity, provide a viable alternative for fixed restoration in the posterior region.

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