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Original Research Article

Mechanical Properties of Different Dentin Replacement Materials: A Comparative Study of Biaxial Flexural Strength and Microhardness

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ABSTRACT

Aim: Endodontically treated teeth (ETT) require restorative materials that can effectively replace lost dentin and withstand occlusal forces. This study aimed to compare the biaxial flexural strength (BFS) and Vickers microhardness (VHN) of four different dentin replacement materials: a high-viscosity resin-modified glass ionomer cement (RIVA light cure HV), a bulk-fill flowable composite resin (SDR flow+), a flowable short fiber-reinforced composite (everX Flow), and a short fiber-reinforced composite (everX Posterior).

Material and Methods: A total of 96 disk-shaped samples were prepared, 24 from each material. Half of the samples were subjected to BFS testing (n=12), while the remaining samples were subjected to microhardness testing (n=12). Statistical analysis was performed using one-way ANOVA and Welch's ANOVA.

Results: everX Flow showed the highest BFS (169.95 ± 10.3 MPa), followed by everX Posterior (141.42 ± 5.41 MPa), SDR flow+ (135.17 ± 4.17 MPa), and RIVA light cure HV (35.13 ± 6.14 MPa). While there was no significant difference between the BFS values of the everX Posterior and SDR flow+ groups ($p>0.05$), there was a difference among the BFS values of the other groups ($p<0.05$). Regarding VHN, everX Posterior group demonstrated the highest hardness values (54.81 ± 4.06), followed by everX Flow (44.89 ± 1.89), RIVA light cure HV (41.19 ± 2.08), and SDR flow+ (22.99 ± 1.61) groups ($p < 0.05$).

Conclusion: Short fiber reinforced composites have favorable microhardness and flexural strength as dentin replacement materials.

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INTRODUCTION

Specialized restorative materials and treatments are required for endodontically treated teeth (ETT) to maintain structural integrity[1], which mainly occurs due to severe caries or trauma necessitating root canal treatment that can lead to the loss of the pulp chamber roof and pericervical dentin. As a result, ETT are more prone to fractures.[2]

When preparing direct restorations for ETT, several options are available to replace the missing dentin. These options include glass ionomer cements (GICs), resin modified glass ionomer cement (RMGICs), conventional packable composite resins, short fiber-reinforced composite resins (SFRC), and dual-cure core build-up composite resins.[3]

Packable SFRC (everX Posterior) is recommended for reinforcing composite restorations where ETTs are subjected to high stress.[4] The flowable version of SFRC (everX Flow) was introduced in 2019, promising easy handling and adaptability, and shows encouraging results in direct restorations across clinical scenarios.[5]

SDR flow+ is a low-stress flowable material that also serves as a dentin replacement material. SDR flow+ features a proprietary, patented, modified urethane dimethacrylate (UDMA) monomer that has a high molecular weight and contains embedded photoactive groups. This composition leads to reduced shrinkage and an improved degree of effectiveness conversion.[6] SDR flow+ is a promising material for dentin replacement, offering several advantages, including superior performance in terms of bond strength and clinical outcomes compared with RMGICs.[7]

Further advancements in GIC chemistry, along with the development of RMGICs, have introduced novel materials for dentin replacement options. One such material is high viscosity glass ionomer cement (HVGIC), which has been developed to improve the weak mechanical properties of conventional GICs and enhance wear resistance against occlusal forces in clinical applications. Additionally, these materials provide an alternative to composite resin and amalgam for permanent tooth restorations. The wear resistance, surface hardness, bending strength, and compression resistance of these cements, which use hardening mechanisms similar to conventional GICs, have been improved.[8]

As such, the question arises of which dentin replacement material would be the best substitute for missing dentin in ETT given that these materials play a crucial role in the direct restoration of ETT. These materials should not only help preserve pericervical dentin but also enhance resistance to lateral forces during mastication, allowing reliable restoration of dental anatomy and supporting overall dental health and survival.[9] For this reason, assessing dentin replacement materials should encompass not only their chemical properties, but also their physical and mechanical characteristics. Although several laboratory tests exist for dentin replacement materials, they only partially simulate clinical performance; however, they can guide an understanding of how a material's properties are affected by modifications to the composition or its processing.

The microhardness test is essential for evaluating dentin replacement materials as it provides insights into their mechanical properties, which are essential for ensuring durability and functionality in dental applications. This test evaluates material hardness relating to their capacity to endure occlusal forces and resist wear over time. The subsequent sections discuss the importance of microhardness testing for materials used to replace dentin.[10]

In another test called the biaxial flexural strength test, flexural forces are generated to simulate clinical situations where materials must withstand flexing, particularly in the posterior region. Although not confirmed clinically, high flexural strength is preferred for materials that can experience cracking under occlusal forces.[11] The biaxial flexure test is essential for dental materials, as it more accurately simulates real loading conditions compared with uniaxial tests. This method assesses the material's fatigue strength and integrity under complex stress conditions, which are crucial for dental applications where materials encounter multidirectional forces. The test evaluates the tensile and compressive stresses that converge, ensuring that replacement materials can endure the mechanical requirements of the oral environment, resulting in enhanced durability performance.[12]

Therefore, the purpose of this study was to analyze and compare the biaxial flexure strength and microhardness of different dentin replacement materials. The first research hypothesis was that dentin replacement materials would differ in microhardness, and the second research hypothesis was that the tested materials would differ in flexural strength.

MATERIAL AND METHODS

The four different material types investigated in this study are HVGIC (RIVA light cure HV), flowable bulk fill composite resin (SDR flow+), flowable SFRC (everX Flow), and packable SFRC (everX Posterior), are presented in Table 1. The sample size was calculated using G*Power (version 3.1.9.7, Kiel University, Kiel, Germany) and a one-way analysis of variance (ANOVA) based on findings from a published study.[13] The effect size (f) was 0.5, the type I error (α) was 0.05, and the statistical power (1-β) was 0.80. The total sample size required for the microhardness test was 48, with each group requiring a minimum sample size of 12.

Table 1. Materials used in the study.

Material	Manufacturer	Composition	Lot number
EverX Flow, flowable short fiber-reinforced composite	GC Corporation, Tokyo, Japan	Micrometer scale glass fiber filler, barium glass, 70 wt%, 46 vol% Bis-EMA, TEGDMA, UDMA.	2106221
EverX Posterior, short fiber-reinforced composite	GC Corporation, Tokyo, Japan	Shot E-glass fiber filler, Barium glass 74.2 wt%, 53.6 vol% Bis-GMA, PMMA, TEGDMA.	2308071
SDR flow+ (SDR), smart dentin replacement	Dentsply-Sirona, Milford, USA	Modified UDMA, TEGDMA, EBPADMA, Barium borosilicate glass 68 wt%, 44 vol%.	1910141
RIVA light cure HV, Resin-modified glass ionomer cement	SDI Limited, Bayswater, Australia	Liquid: HEMA 15–25%, acrylic acid homopolymer 15-25%, dimethacrylate cross-linker 10-25%, acidic monomer 10–20%, tartaric acid 1-5%. Powder: Fluoro-aluminosilicate glass 93-100% Ratio: 0.43/0.13 (g/g) powder/liquid	1205309

24 disc-shaped samples (0.5 mm thick and 6 mm in diameter) of each material, a total of 96, were prepared using silicone molds. The SFRC materials and SDR flow+ were prepared as per the manufacturer's guidelines and placed into molds. The RIVA light cure HV capsule was activated and mixed using an amalgamator and placed into the mold using a capsule applicator. For all the materials, the mold was filled slightly above the top. A glass plate was then placed over the materials before it set to create a smooth surface. Then, the materials were polymerized for 20 sec using an LED curing unit (Elipar S10, 3M, St Paul, MN, USA) with an output intensity of 1200 mW/cm^2. The tests were conducted after all prepared materials were incubated at 100% humidity and at 37°C for 24 h.

A Universal Testing Machine (Model 4469, Instron Ltd., High Wycombe, UK), operating at a crosshead speed of 1 mm per minute, was used to determine the biaxial flexural strength of half of the discs in each group (n=12). The samples were positioned in a custom-made jig. The load, intended to induce fracture, was applied perpendicularly to the sample's surface at its center, with a stainless-steel rod with a radius of 1 mm at the point of contact. The fracture load was recorded and for each sample, the biaxial flexural strength was calculated using the formula:

$$S=0.2387\ F(X-Y)/d^2$$

where S represents the maximum tensile stress (MPa) at the center of the disc, F denotes the total load (N) that causes fracture, d indicates the thickness of the sample (mm) at the load application site, and X and Y are the products of the formula:

$$X=(1+v)\ \ln(r2/r3)^2+[(1-v)/2](r2/r3)^2$$

$$Y=(1+v)[\ln(r1/r3)^2]+(1-v)(r2/r3)^2\ ,$$

where r1 is the radius of the supporting circle (5.2 mm), r2 is the radius of the loaded area (1 mm), and r3 is the radius of the disc sample (6 mm). v is Poisson's ratio (used v=0.25). The biaxial flexure strength values of all samples were calculated and recorded in MPa.

The remaining samples for each group (n=12) were placed in a microhardness test device (HMV-G20S, Shimadzu Corp., Kyoto, Japan). Three indentations were equally spaced over a circle, with each being no closer than 0.5 mm to the adjacent indentation, using a 50 g load for a dwell time of 15 seconds. The two diagonal lengths of each indentation were measured using a built-in scale microscope with ×40 magnification and were converted into a microhardness value (VHN) using the equation:

$$HV=1.854\ P/d^2\ ,$$

where HV represents microhardness in kg/mm^2, P denotes the load in kg-force, and d refers to the average length of the diagonals in mm. For a given sample, the three hardness values for each surface were averaged and reported as a single value (Figure 1).

Statistical analysis

Statistical analysis was performed using IBM SPSS V23 software (SPSS Inc., Chicago, IL, USA). The Shapiro–Wilk test was used to analyze the conformity of the values to normal distribution. Levene's test

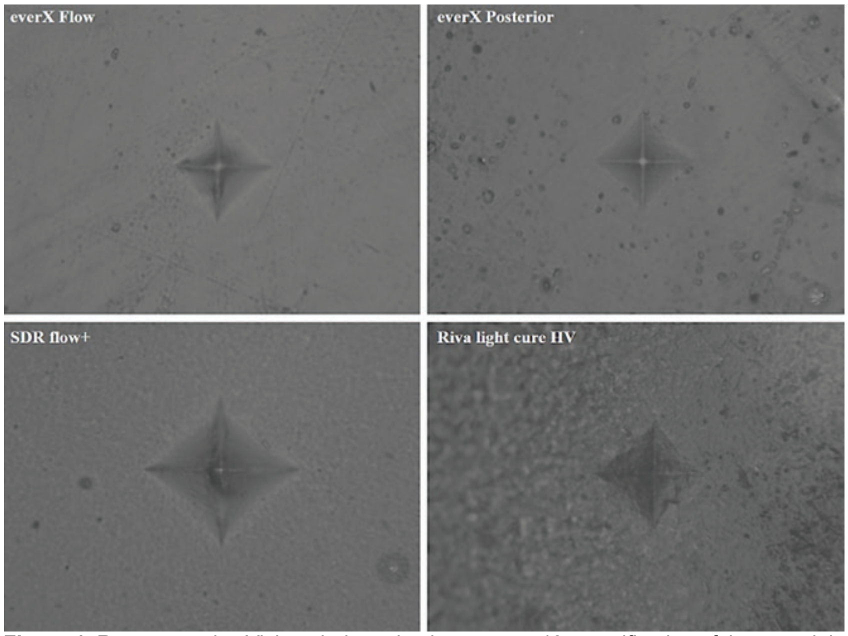

Figure 1. Representative Vickers indentation images at ×40 magnification of the materials

was used to assess whether the variances were homogeneous. One-way analysis of variance (ANOVA) was used to compare the biaxial flexural strength values among the materials when variances had homogeneous distribution. Welch's ANOVA test was used to compare the microhardness values among the materials when non-homogeneous distribution of variances was observed. Tukey's honestly significant difference (HSD) post-hoc test was used for pairwise comparisons.

RESULTS

Figure 2 presents the means and standard deviations of the restorative material groups. One-way ANOVA results suggest that the biaxial flexural strength differs among the materials ($p<0.001$). Tukey's HSD post hoc test showed the highest biaxial flexural strength values in the everX Flow group (169.95±10.3 MPa), followed by the everX Posterior (141.42±5.41 MPa), SDR flow+ (135.17±4.17 MPa), and the RIVA light cure HV (35.13±6.14 MPa) groups ($p<0.05$). The mean biaxial flexure strength values of the everX Posterior and SDR flow+ groups were not significantly different ($p=0.37$).

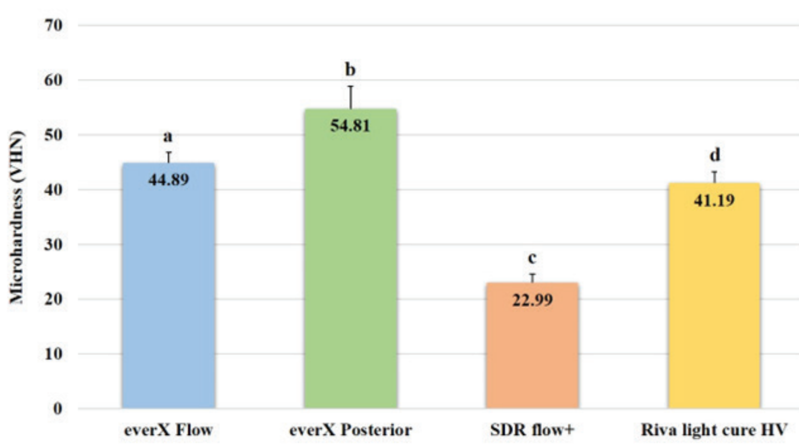

Figure 2. The mean microhardness values (VHN) and standard deviations of the groups.
a–d: Different lowercase letters indicate significant differences between groups.
(one-way ANOVA/Test statistic: 686.138/p < 0.001).

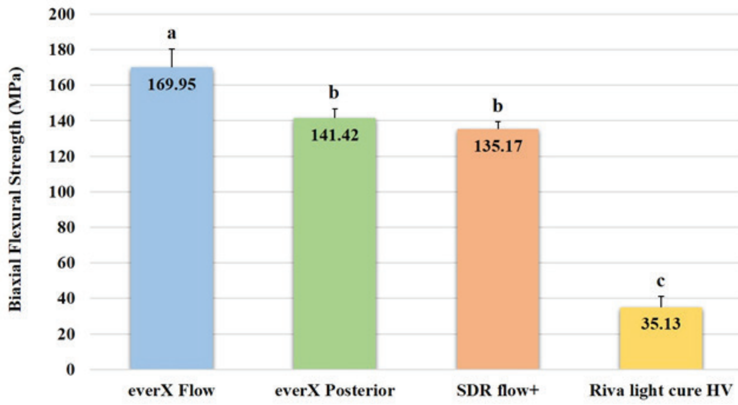

Figure 3. The mean biaxial flexure strength values (MPa) and standard deviations of the groups. a–c: Different lowercase letters indicate significant differences between groups. (Welch's ANOVA/Test statistic: 356.894/p < 0.001).

Figure 3 shows the means and standard deviations of Vickers microhardness values for the groups tested. Welch's ANOVA test showed a significant difference in microhardness values between the groups (p<0.001). Tukey's HSD post hoc test revealed that the highest microhardness values were in the everX Posterior group (54.81±4.06 VHN), followed by everX Flow (44.89±1.89 VHN), RIVA light cure HV (41.19±2.08 VHN), and the SDR flow+ (22.99±1.61 VHN) groups (p<0.05).

DISCUSSION

Natural dentin features a complex structure that provides flexibility and resilience, so any replacement materials should aim to replicate these properties.[14] Many types of materials have been introduced into the dental market to substitute lost dentin, with each type possessing unique characteristics related to chemistry, biocompatibility, ease of placement, and mechanical properties.

There are both direct and indirect methods to determine the physical properties of resin. Direct methods involve measuring the amount of monomer, whereas indirect methods can make comparisons based on microhardness.[15] Microhardness is a physical property that reveals material characteristics and signifies the amount of force a material can endure before experiencing permanent deformation when this force is applied to a small area.[16] Therefore, this study used the Vickers microhardness test to assess the tested materials. Regarding the results of the microhardness test, there was a statistically significant difference among all materials tested; therefore, the first research hypothesis was accepted.

When considering the three composite materials tested, everX Posterior with a filler rate of 74.2 wt% and 53.6 vol% showed the highest microhardness values. Several factors can influence the hardness of dentin replacement materials, including the size, shape, and proportion of fillers in the inorganic phase. Hardness typically increases with filler content because as the volume fraction of filler increases, a point is reached where particles make mutual contact within the matrix, and beyond this threshold, stress primarily transfers through particle–particle interactions within the material.[17] In addition, the microhardness values of everX Flow with a filler content of 70 wt% and 46 vol% were higher than for SDR flow+ with a filler load of 68 wt% and 44 vol%. These results are consistent with studies indicating a relationship between filler rate and the surface hardness of resin-based materials.[17,18]

The chemical composition of the matrix also enhances microhardness by influencing the viscosity of the material.[19] Strong intramolecular hydrogen bonds between hydroxyl groups characterize Bis-GMA, which is recognized as the least flexible and most viscous of all dental resin monomers. Bis-GMA, which has a molecular weight five times that of methyl methacrylate and enhances toughness via extensive crosslinking, is a bulky and structurally rigid monomer commonly used in dental resin composites and adhesives.[20] Conversely, UDMA is a viscous resin monomer composed of carbonyl and amine groups that are joined by hydrogen bonds, has a much lower viscosity than Bis-GMA due to poor hydrogen bonding.[19] The lack of UDMA in everX Posterior might explain why it exhibited the highest microhardness values compared with materials without UDMA.

Of note, high viscosity RMGICs had higher microhardness results than SDR flow+. With a higher filler rate expected to lead to an increase in mechanical properties, the hardness of most GICs can be improved by increasing the powder to liquid ratio and reducing the particle size of the fillers.[21] RIVA light cure HV (4.7:1.4 powder to liquid) used in this study has a high ratio among the GICs, which might be associated with differing microhardness values of these materials. To the best of our knowledge, there is no study that compares the microhardness and biaxial flexural strength of the materials tested in this study. However, low microhardness values of SDR flow+ compared with other resin-based materials are supported by a recent study.[22]

Vickers microhardness refers to a material's surface resistance to plastic deformation after indentation or penetration. Studies indicate that the microhardness values for sound dentine range from 37 to 60 VHN according to localization.[23,24] The optimal hardness of a dentine replacement material should be within the same range as dentin;[25] therefore, these findings suggest that SFRC materials and RMGICs might have hardness similar to human dentin, whereas SDR flow+ appears to be less durable regarding chewing forces and might be better suited for restorations exposed to lower occlusal forces. Although SDR flow+ material should exhibit better microhardness values to simulate dentin (particularly in high-load areas), a dentin replacement material must also possess adequate flexibility to absorb stress alongside high strength. Therefore, in addition to the Vickers microhardness test, the samples were subjected to the biaxial flexural strength test in this study.

The flexural strength of dental materials refers to a material's ability to resist deformation and fracture when subjected to a bending force. This mechanical property helps predict how well a dental material will perform under masticatory forces, and this value is desired to be equal to or greater than the flexural strength of dentin. Although factors such as age, tubule orientation, and mineral content considerably affect these values, the flexural strength of human dentin is generally reported to range from 100 to 200 MPa.[26–28] In the biaxial tests conducted in this study, the force was loaded from the middle of the circular disc-shaped samples and more homogeneously to the sample. The direction of forces applied to restorative materials is generally multiaxial; therefore, biaxial tests mimic functional forces better than uniaxial tests. Since the test samples were prepared in a disc shape, they had lower sensitivity to edge flaws. Additionally, using small samples has the advantage of being easier to prepare and requiring less material. In the current study, the highest biaxial strength value was seen in everX Flow (169.95 MPa), followed by everX Posterior (141.42 MPa), SDR flow+ (135.17 MPa), and RIVA light cure HV (35.13 MPa). As such, the second research hypothesis was accepted.

The incorporation of glass-fiber fillers into composite formulations has been shown to improve mechanical properties, such as tensile load capacity, fracture toughness, and compressive strength, and it has been reported that these materials can effectively mimic the mechanical properties of dentin.[29] Glass fibers act as load carriers within the composite matrix. When external forces are applied, these fibers help absorb the load and dissipate energy more evenly across the material. Additionally, glass fibers can bridge cracks that form under stress, preventing them from propagating further.[4] These properties ensure that the fibers effectively contribute to the overall strength of the composite. Two types of fiber-reinforced composites were used in this study: one containing micrometer-scale glass fibers (everX Flow) and the other containing millimeter-scale glass fibers (everX Posterior). everX Flow had higher flexural strength than SDR flow+ (without fiber reinforcement), while no difference was found between everX Posterior and SDR flow+. The finding that the flexural strength of everX Flow is greater than SDR flow+ is consistent with a study that evaluates uniaxial flexural strength.[30] Similarly, in our previous fracture resistance study, we found higher strength values in teeth restored with everX Flow compared with SDR flow+.[31]

The type, size, and distribution of fillers greatly affect the mechanical properties of dental materials. It has been reported that the flexural strength of resin composites containing more filler loading, both in volume and weight, increases.[21,32] However, in this study, everX Flow had improved biaxial flexural strength values compared with everX Posterior that has high-volume filler loading, which might be due to the smaller micrometer-scale glass fiber filler of everX Flow. This study is consistent with the study of Garoushi *et al*,[33] who showed no direct relationship between the volumetric concentration of fillers and the uniaxial flexural strength of the material. Additionally, a recent study reported that everX Flow had greater toughness than everX Posterior in samples prepared with 2 mm thickness. As the sample thickness increased, the toughness of everX Posterior increased to become similar to everX Flow. Therefore, everX Flow is more suitable than everX Posterior in terms of fracture resistance in shallow cavities.[34] To the best of our knowledge, there is no study comparing the flexural strength of everX Posterior and SDR flow+. An important result of this study is that SDR flow+ exhibits similar flexural strength to everX Posterior despite having a lower filler volume, being a more flowable structure, containing UDMA instead of Bis-GMA in the resin matrix, and not containing glass fibers. We assume that this situation could be due to the thinner preparation of the samples in the biaxial flexural strength test.

In their study, Ong *et al*.[35] reported the flexural strength of the resin-based bulk-fill composite (Filtek Bulk-fill Posterior, 3M ESPE, St Paul, MN, USA) as approximately 160 MPa, while RIVA light cure HV was 40 MPa in artificial saliva. Similarly, despite different sample preparation and testing methods, the biaxial flexural strength of RIVA light cure HV (35 MPa) was lower than the bulk fill composites used in this study. In this study, the flexural strength of high viscosity RMGIC cement was 3.8 times lower than bulk-fill flowable composite (SDR flow+). This result is consistent with Ramos *et al*.[36] who found that the flexural strength of RIVA light cure HV was 3.5 times lower than that of bulk-fill flowable composite (Filtek Bulk Fill Flow, 3M).

The lower flexural strengths of RMGIC compared with composites can be attributed to several intrinsic material properties and structural differences. RMGICs generally exhibit weaker mechanical properties due to their composition, such as lower filler ratio and irregular filler particles or setting mechanisms, which differ significantly from those of resin composite materials.[37] RMCISs are reinforced with glass particles, but their low filler ratio and irregular filler particles reduce the mechanical properties of the material. Furthermore, the bond strength between the glass and the resin matrix is limited, which leads to inefficient load transfer and hence, low mechanical strength. According to ISO 4049:2019; type 1, the flexural strength for all polymer-based restorative materials should achieve a minimum value of 80 MPa.[38] According to the results of this study, everX Flow, everX Posterior, and SDR flow+ all met the expected flexural strength of dentin replacement materials. However, the flexural strength of RIVA light cure HV was insufficient for use as a dentin replacement material.

The major limitation of this study was that the microhardness of the samples at various depths was not evaluated. Additionally, further *in vivo* studies should be conducted in the oral cavity to provide results that assess the durability of dentin replacement materials.

CONCLUSION

Within the limitations of this study, it is recommended that RIVA light-cure HV be carefully evaluated for use in Class 1 and 2 restorations in areas with high chewing forces, in core buildups, and in patients with parafunctional habits, given the material's low flexural strength. While everX Flow offers advantages as a dentin replacement restoration with its high flexural strength, everX Posterior offers higher hardness and should provide long-term durability in extensive posterior restorations. The choice of restoration material should be made according to the specific clinical requirements and the location of the restoration.

CONFLICTS OF INTEREST STATEMENT

The authors declares no conflicts of interest.

Farklı Dentin Replasman Materyallerinin Mekanik Özellikleri: Çift Eksenli Eğilme Dayanımı ve Mikrosertlik Üzerine Karşılaştırmalı Bir Çalışma

ÖZET

Amaç: Endodontik olarak tedavi edilen dişler (ETT), kaybedilen dentinin yerini etkili bir şekilde alabilecek ve oklüzal kuvvetlere dayanabilecek restoratif materyallere ihtiyaç duyar. Bu çalışmanın amacı dört farklı dentin replasman materyalinin [yüksek viskoziteli rezin modifiye cam iyonomer siman (RIVA light cure HV), bulk-fill akışkan kompozit rezin (SDR flow+), akışkan kısa fiberle güçlendirilmiş kompozit (everX Flow) ve kısa fiberle güçlendirilmiş kompozit (everX Posterior)] çift eksenli eğilme dayanımı (BFS) ve Vickers mikrosertliğini (VHN) karşılaştırmaktır:

Gereç ve Yöntem: Her materyalden 24 adet olacak şekilde toplamda 96 adet disk şeklinde örnek hazırlandı. Örneklerin yarısı BFS testine tabi tutulurken (n=12), kalan örneklere mikrosertlik testi uygulandı (n=12). İstatistiksel analiz tek yönlü ANOVA ve Welch's ANOVA kullanılarak gerçekleştirilmiştir.

Bulgular: everX Flow en yüksek BFS'yi (169,95 ± 10,3 MPa) gösterirken, bunu everX Posterior (141,42 ± 5,41 MPa), SDR flow+ (135,17 ± 4,17 MPa) ve RIVA light cure HV (35,13 ± 6,14 MPa) izlemiştir. everX Posterior ve SDR flow+ gruplarının BFS değerleri arasında anlamlı bir fark bulunmazken ($p>0,05$), diğer grupların BFS değerleri arasında fark vardır ($p<0,05$). VHN açısından, everX Posterior grubu en yüksek sertlik değerlerini (54.81 ± 4.06) gösterirken, bunu everX Flow (44.89 ± 1.89), RIVA light cure HV (41.19 ± 2.08) ve SDR flow+ (22.99 ± 1.61) grupları izlemiştir ($p < 0.05$).

Sonuç: Kısa fiber takviyeli kompozitler, dentin replasman materyalleri olarak uygun mikrosertlik ve eğilme dayanımına sahiptir.

Anahtar Kelimeler: Dentin replasman materyali; Eğilme dayanımı; Kısa fiber takviyeli kompozit; Mikrosertlik; Rezin modifiye cam iyonomer siman

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