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FRACTURE RESISTANCE, FINITE ELEMENT ANALYSIS AND WEIBULL RISK OF FAILURE FOR ENDODONTICALLY TREATED MOLARS RESTORED WITH LITHIUM DISILICATE AND HYBRID CERAMIC ENDOCROWNS WITH TWO PREPARATION DESIGNS

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ABSTRACT

Objective: The present study aimed at evaluating the fracture resistance of endodontically treated molars restored using IPS e.max CAD (e.max CAD) and Enamic endocrowns using two preparations designs after thermomechanical fatigue.

Materials and methods: 40 intact mandibular molars were selected and endodontically treated following a standardized procedure. Molars were decapitated 3.5mm coronal to the cervical line then embedded in epoxy resin blocks. Samples received standardized preparations for endocrowns including the preparation of the pulp chamber, then they were divided into two groups; group 1 where No-Ferrule was included in the preparation and group 2 with 2.5mm Ferrule extracoronally. Each group was further divided into two subgroups according to the material used for constructing endocrowns; e.max CAD endocrowns and Vita Enamic endocrowns. Endocrowns were constructed using Cerec CAD/CAM machine. Constructed endocrowns were adhesively bonded to their respective teeth then subjected to a thermomechanical fatigue procedure (49N, 1.6Hz, 120,000cycle, 5^o-55^o C) in a chewing simulator. The fracture resistance of each sample was determined by subjecting the samples to a static compressive load until failure. Failure loads were recorded as an indication of fracture resistance. Stresses at failure were analyzed using finite element analysis (FEA) and failure probability percentage was evaluated using Weibull risk of failure. Data were collected, tabulated and statistically analyzed.

Results: For fracture resistance, the highest fracture load values were recorded with samples of Ferrule with e.max CAD endocrowns, followed by samples of No-Ferrule with e.max CAD endocrowns and then samples of Ferrule with Enamic endocrowns. The lowest fracture load values were recorded with samples of No-Ferrule with Enamic endocrowns. The magnitude of stresses

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generated in different parts of the samples as reveled by FEA generally followed a different order than in the fracture resistance. Weibull Risk of failure showed that samples of No-Ferrule with Enamic endocrowns had the highest failure probability especially under high loads.

Conclusions: Ferrule design would improve the fracture resistance of endodontically treated teeth especially when restored with lithium disilicate based (e.max CAD) endocrowns. Under low magnitude of forces, both materials would work safely with either design.

INTRODUCTION

The higher risk of biomechanical failure usually associated with endodontically treated teeth (ETT) represents a common problem in restorative dentistry.[1] The altered physical characteristics of ETT including changes in collagen cross linking and dehydration of the dentin, results in 14% reduction in their strength and toughness.[2] in addition to approximately 9% internal moisture loss. The combined loss of structural integrity, loss of moisture and loss of dentin toughness compromise ETT and causes difficulties in their restoration.[3]

Moreover, the loss of tooth structure associated with caries, trauma and extensive cavity preparation of ETT increases the risk factors and compromises the prognosis of these teeth.[4] It was found that endodontic procedures, occlusal cavities and MOD cavities reduce the strength of ETT by 5%, 20% and 63%, respectively.[5]

Consequently, the amount of sound tooth structure that remains following root canal therapy and any subsequent preparation is an important factor in selecting the suitable line of treatment for ETT.[6] The vulnerability of ETT to fracture led to the assumption that the best line of treatment would be post retained restorations.[7] However, irrespective of the post material used; being metal based or fiber reinforced; posts have often been described as not to reinforce ETT.[8] Post placement could interfere with the mechanical resistance of ETT, increasing the risk of damage to residual tooth structure.[9]

Moreover; restoring ETT using post retained restorations includes more than one potential component-to-component interfaces.[10]

A biomechanical study found increased failure potential in concomitance with increased number of interfaces.[11] Stress concentrations at the interface between the post, core, luting cement and the reconstructed crown may cause failure because of the significant strain gradient caused by the difference in stiffness between different components.[12] Posts were thus regarded as a mean of retention only for the definitive permanent restoration without being involved in improving the mechanical behavior of ETT.[1]

In addition, post retained restorations represent a major risk factor for the integrity of tooth structure; as in cases of excessive loss of coronal hard tissue, limited inter-arch space, and dilacerated, calcified or short roots. Hence, a new line of treatment for ETT was proposed taking advantage of the rapidly developing adhesive procedures which eliminated the use of macroretentive features (i.e. radicular posts) if enough surfaces for bonding is available.[13] Accordingly, the insertion of radicular posts became the exception rather than the rule. In fact, minimally invasive preparations, with maximal tissue conservation, are now considered 'the gold standard' for restoring ETT.[14] Based on these assumptions, endocrowns were introduced as a line of treatment for ETT, replacing radicular posts in several situations.

The endocrown is a monolithic ceramic crown restoring devitalized tooth, anchored to the internal portion of pulp chamber and cavity margins, thus obtaining macromechanical retention (provided by the pulpal walls) and microretention through using adhesive cementation.[15] The preparation design for endocrown comprises a cervical circumferential butt margin and a central retention cavity inside the pulp chamber, with or without a ferrule, and constructs both the crown and core as a single unit.[16,17] In vitro studies have reported that bonded endocrowns show fracture load values comparable to those of classical crowns.[18] Several clinical case reports have shown the potential of this restorative approach to provide adequate function and esthetics, even with the compromised tooth integrity of non-vital molars.[19,20]

Being dependent on micromechanical adhesion in its retention; the longevity of endocrown is directly related to the selection of constructing material which should therefore bear the capacity of promoting adhesion when using the suitable bonding cement.[20–22] That's why reinforced, acid etchable dental ceramics were suggested as the materials of choice for the fabrication of endocrowns, since they guarantee the mechanical strength needed to withstand the occlusal forces exerted on the tooth, as well as the capability of being adhesively bonded to the cavity walls.[17,23,24]

Moreover, Lim et al [10] suggested that the elastic modulus of the definitive restoration is the primary factor that influences the stress distribution of ETT and hence the stress concentration at the coronal structure could be lowered through the use of a definitive restoration with high elastic modulus. Furthermore, endocrowns fabricated with indirect composite resin based materials seem also to be a reliable restoration, because the dentin like elastic modulus generates low amounts of stress concentration and thus improves the durability of the restoration.[19]

Accordingly, an in vitro study, assessing fracture resistance and marginal leakage of endocrowns used 3 different CAD/CAM fabricated ceramic endocrowns including feldspathic porcelain, lithium disilicate ceramic and resin nano-ceramic on maxillary molars was conducted. The study showed that resin nano-ceramic endocrowns have significantly higher fracture resistance and more favorable fracture mode, but also higher dye penetration and more microleakage than feldspathic porcelain and lithium disilicate endocrowns.[25]

Cyclic load fatigue has been understood to be an important concept, rather than a single catastrophic event, for inducing ceramic restoration failure. The clinical significance of the results from static load application is sometimes questionable because a monotonic load does not represent the clinical situation where repetitive fatigue loading is characteristic. Therefore, predicting the fatigue lifetime is more realistic than only considering the static distribution of the stress state for ceramic restorations.[26]

It has been shown that the presence of at least 2mm circumferential ferrule improves fracture resistance of ETT.[27] With the recent adhesive techniques, creating a ferrule could be a drawback because of loss of natural tooth structure and enamel.[4] However, studies that paid attention to the effect of different preparation designs on the fracture resistance of endocrowns were very limited.

The present study was therefore proposed to investigate fracture resistance of endocrowns designed with or without a ferrule and fabricated using two different materials; lithium disilicate based ceramic and hybrid ceramic after thermomechanical fatigue. The null hypothesis assumed that there will be no difference in fracture resistance of endocrowns designed with or without ferrule, made from e.max CAD and Enamic; after thermo-mechanical fatigue. Analysis of failure using finite element analysis (FEA) and failure probability using Weibull risk of failure are also to be investigated.

MATERIALS AND METHODS

The materials used in the current study are listed in Table 1.

Table (1) Materials used in the current study.

Material	Composition	Batch No.	Manufacturer
IPS e.max CAD	Standard composition; SiO_2 Li_2O K_2O P_2O_5 ZrO_2 ZnO Al_2O_3 MgO Colouring oxides	U15876	Ivoclar Vivadent, Schaan, Liechtenstein
Enamic	Ceramic part 75 vol% SiO_2 Al_2O_3 Na_2O K_2O B_2O_3 ZrO_2 CaO Polymer part 25 vol% Urethane dimethacrylate (UDMA) Triethylene glycol dimethacrylate (TEGDMA)	40880	Vita, Vita Zahnfabrik, Bad Säckingen, Germany
Rely X Unicem Clicker	Base paste Methacrylate monomers containing phosphoric acid groups Methacrylate monomers Silanated fillers Initiator components Stabilizers Catalyst paste Methacrylate monomers Alkaline (basic) fillers Silanated fillers Initiator components Stabilizers Pigments	342210	3M ESPE, St Paul, MN, USA

To conduct the present study, forty intact, mandibular sound, caries and crack free first molars freshly extracted for periodontal problems from 50-60 years old patients were selected. The size of the selected teeth were standardized by measuring (in millimeters) the bucco-lingual and mesio-distal widths at the cementoenamel junction (CEJ) using digital electronic caliper* The bucco-lingual dimension of the selected teeth was approximately 12±1mm and while their mesio-distal dimension was approximately 11±1mm.

The molars were then sectioned perpendicular to their long axes 3.5mm coronal to their CEJ at the distal surface using a diamond disc** mounted on a slow speed hand-piece. Only molars with almost rectangular outlined pulp chambers were included in the present study. The selected molars were then stored in distilled water to avoid dehydration.

Endodontic procedures:

All teeth were endodontically prepared to the full working length using rotary Protaper files S1, S2, and F1 respectively (Dentsply Maillefer, Switzerland) mounted on an X-Smart micro motor***, at a speed of 250 rpm. The canals were irrigated with 2.5% sodium hypochlorite between different files then dried using paper points****. The canals were obturated by lateral condensation technique using Protaper gutta-percha cones[B] and eugenol free sealer*****.

The excess coronal gutta-percha was then removed to about 1mm apical to the orifice of each canal, then flowable composite****** was used to fill the canals up to the level of the pulp chamber floor.[25] Samples were then stored at 37°C for 72 hours to ensure complete setting.

Each tooth was then individually embedded with the aid of a surveyor in an epoxy resin block# using PVC rings of 2cm height and 1.5cm internal diameter as molds, so that the long axis of the tooth is aligned parallel to the outer surface of the ring, leaving 2mm apical to the distal CEJ exposed.

Endocrown Preparation:

Two designs of endocrowns were tested in this study, with no and with ferrule preparation; No-Ferrule design and Ferrule design, respectively. Accordingly, the selected teeth were randomly divided into 2 equal groups; 20 teeth each. To standardize teeth preparation for both designs, crowns of teeth were prepared using a special milling machine.## The machine assembly incorporates a slow-speed straight hand-piece perpendicular to the machine platform.

The intracoronal preparation of all teeth of both designs was limited to the removal of the residual pulp chamber roof and excessively undercut areas. This is in addition to aligning the axial walls with an internal taper of 8-10^{o} leaving sufficient axial dentinal wall. This is to ensure that after ferrule preparation with 1mm finish line thickness at least 1mm thickness of axial dentin exists. Intracoronal preparation was made in respect to the limits of the anatomical configuration of teeth pulp chambers. Teeth to receive endocrowns with No-ferrule design had extracoronal preparation ending with a

* 0-20cm; Mitutoyo Corporation, Tokyo, Japan
** Dentsply, Maillefer, Switzerland
*** Dentsply, DeTrey, Germany
**** META BIOMED Co,. Ltd., Korea
***** AH Plus, Dentsply, DeTrey, Germany
****** Filtek Z350XT flowable, 3M ESPE, St Paul, MN, USA
# Kemapoxy 150, CMB International, Egypt
Centroid CNC, milling machine, USA

butt joint 3.5mm coronal to the distal CEJ with no ferrule prepared. On the other hand, teeth to receive endocrowns with ferrule design were extracoronally reduced to have ferrule starting 1mm coronal to the distal CEJ. The ferrule was adjusted to be 2.5mm in occluso – gingival height with an external convergence angle of 8-10^{o}. The reduction resulted in forming a 1mm thick circumferential finish line with 90^{o} shoulder margin and rounded internal line angle. All internal and external line angles were rounded and smoothened using a rounded tip stone which was changed for every 5 preparations.

Construction of the endocrowns:

The endocrowns were constructed from either materials; IPS e.max CAD[*] (e.max CAD) or Enamic[**]. Hence, teeth in each category were further subdivided into 2 equal subgroups (n=10).

The prepared teeth in their resin blocks were individually sprayed with light reflecting powder[***], secured on the tray of the inEos scanner[****], and scanned to obtain an optical impression. The CEREC inLab CAD/CAM machine[*****] was used to design and construct all endocrowns using either e.max CAD partially crystallized blocks, or Vita Enamic blocks.

Endocrowns made from e.max CAD were further subjected to a crystallization procedure by heating the partially crystallized constructed endocrowns in Programat furnace[******] and subjecting them to heat treatment protocol recommended by the manufacturer.

Cementation procedure:

Rely X Unicem Clicker adhesive resin cement[#] was used to lute the constructed endocrowns to their respective prepared teeth.

Surface conditioning of the endocrowns:

To promote bonding, the intaglio surfaces of the constructed endocrowns were treated according to their manufacturers' instructions. Acid etching using 5% hydrofluoric acid[##] was conducted to e.max and Enamic endocrowns for 20 seconds and 60 seconds respectively. Then, the endocrowns were cleaned using water spray for 60 seconds and dried with oil-free air for 20 seconds. Silane coupling agent[###] was applied to the etched intaglio surfaces of all samples for 60 seconds and then air dried.

Cementation procedure:

Rely X Unicem Clicker adhesive resin cement was used according to the manufacturer's instructions under constant static load of 5kg was maintained using load applicator until complete curing of the cement.

Thermomechanical fatigue:

A thermomechanical fatigue procedure was conducted using a chewing simulator[####] integrated with thermocycling protocol operated on servo-motor. The procedure included the application of a load of 49N in the center of the occlusal surface for 120,000 cycles. Each cycle included a vertical movement of 2mm, a horizontal movement of 3mm

* Ivoclar Vivadent, Schaan, Liechtenstein
** Enamic Vita, Vita Zahnfabrik, Bad Säckingen, Germany
*** Cerec propellant powder, Vita Zahnfabrik, Bad Säckingen, Germany
**** inEos Scanner, Sirona, Bensheim, Germany
***** Sirona, Bensheim, Germany
****** P300, Ivoclar Vivadent AG, Lichenstien, Germany
# 3M ESPE, St Paul, MN, USA
Ultradent, South Jordan, Utah, USA
3M ESPE, St Paul, MN, USA
Robota, AD-TECH Technology CO., Germany

at a frequency of 1.6Hz. Simultaneously, samples were subjected to thermocycling between 5°C and 55°C with a dwell time of 60 seconds; Figure 1.

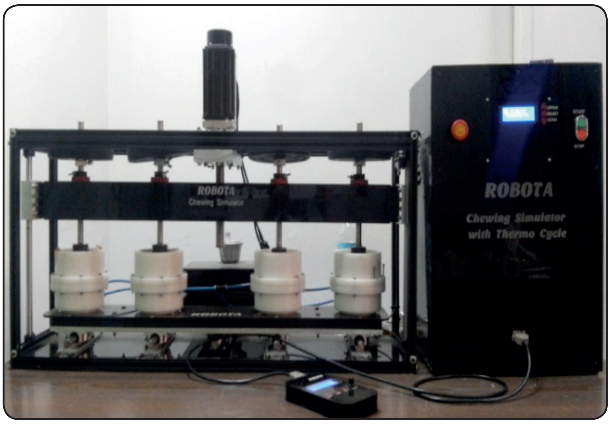

Fig. (1) The chewing simulator with chambers containing some samples.

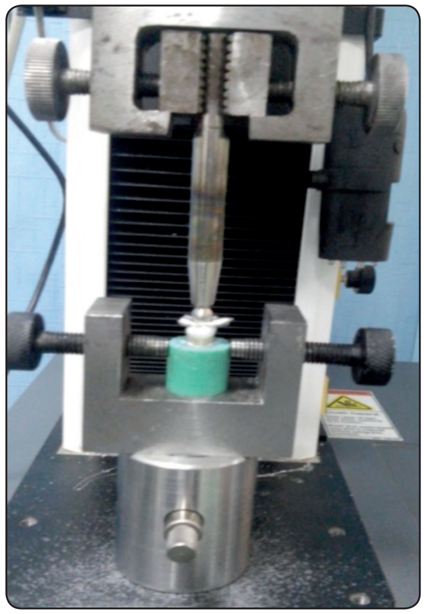

Fig. (2) A sample in the universal testing machine.

Fracture resistance test:

Each sample was individually mounted and secured to the lower fixed compartment of a computer controlled mechanical testing machine* with a load-cell of 5kN. Fracture resistance test was done by compressive mode of loading applied axially to the occlusal surface at the middle of the occlusal surface using a metallic rod with a spherical tip (5.6mm diameter) attached to the upper movable compartment. Testing was conducted at cross-head speed of 1mm/min. A tin foil sheet with a thickness of 0.5mm was placed between the testing rod and the endocrowns to achieve homogenous stress distribution and minimize transmission of local force peaks.[28] The load value at failure manifested by an audible crack and confirmed by a sharp drop at load-deflection curve was recorded in Newton using computer software**; Figure 2.

Finite element analysis (FEA):

To analyze stress distribution and the possible cause of mechanical failure in all examined samples, finite element analysis has been done. Models of the tested groups were built up according to their measured dimensions using SolidWorks software*** running on an ACER computer with Intel ® Core™ i5 – 430M processor (2.26GHz, 3MB L3 cache). The model of each group was subjected to normal compressive force of magnitude equivalent to the recorded failure load obtained from the mechanical fracture resistance test and applied at the mid pint of the occlusal surface of the endocrowns. All built models and their materials were considered homogeneous, linear-elastic and isotropic. The mechanical properties of the tested materials, in terms of elastic modulus (E), Poisson's ratio (υ), density (ρ), tensile and compressive strengths, and their references are tabulated in Table 2.

* Instron, Norwood, MA, USA
** Instron® Bluehill Lite Software
*** SolidWorks ® Premium 2013 x64 Edition

TABLE (2) Materials' properties and their values used for FEA simulation modeling.

		Materials' mechanical properties, units and references					
		E (*GPa*)	*υ*	ρ (*g/cm³*)	*Tensile strength* (*MPa*)	*Compressive strength* (*MPa*)	*References*
Materials used	*e-max CAD*	95	0.25	2.5	43.4	530	[29–31]
	Vita Enamic	30	0.23	2.1	45.06	157	[32–34]
	Dentin	18.6	0.31	2.2	53.37	285	[26,35–37]
	Rely X cement	6.3	0.3	1.7	49.9	244	[38–40]
	Epoxy resin	10.5	0.3	1.95	19.61	73.55	[41–43]
	Polypropylene	1.5	0.45	0.9	31	40	[44–46]

Weibull risk of failure:

Weibull risk of failure for different models was used to measure their failure probability (P_f) using Weibull cumulative distribution function.[26,47]

$P_f = 1 - P_s$

Where P_s is the survival probability and is calculated from:

$P_s = - \exp [-(\sigma/\sigma_0)^m]$

Where σ is any given stress value, σ_0 is the characteristic strength of the model and m is the Weibull modulus. For the investigated models, σ_0 and m where calculated according to DORNER, 1999,[48] and Nwobi and Ugomma, 2014.[49]

Statistical analysis

Data were collected, coded, tabulated and statistically analyzes using the Statistical Package for Social Science (IBM SPSS) version 20. Data were presented as means, and standard deviations. The comparison between the four subgroups regarding quantitative data was done by using one way analysis of variance (ANOVA) test. The Results were considered statistically significant at p-value less than or equal to 0.05 (*$p \leq 0.05$*). For statistically significant results, Bonferroni Post Hoc test was conducted to detect the differences among the subgroups.

RESULTS

Means values (in Newton) and standard deviations of load at failure as an indication of fracture resistance of the tested samples are represented in Table 3 and Figure 3.

Results of the tested subgroups revealed that e.max CAD endocrowns with Ferrule showed the highest mean fracture load value, followed by e.max CAD endocrowns with No-Ferrule which was about 81% that of the former. The third lower value was recorded with Enamic endocrowns with Ferrule and it was about 60% from the highest recorded mean fracture load value, while the Enamic endocrowns with No-Ferrule showed fracture resistance only 38% of the highest recorded value. The differences between all subgroups were statistically significant. The effect of design solely was investigated by T-Test which revealed that No-Ferrule design had mean load of failure only 74.2% that of ferrule design, and this difference was significant. The material effect on load values was also investigated; Enamic endocrowns showed mean load of failure 54% that of e.max CAD, and also this difference was significant.

TABLE (3) Load at failure mean values (N) ± standard deviation (SD) for the tested subgroups.

Design	No-ferrule		Ferrule		P value
Material	e.max CAD	Enamic	e.max CAD	Enamic	
Mean load values (±SD) at fracture	Mean ± (SD)	Mean ± (SD)	Mean ± (SD)	Mean ± (SD)	
	1537.27[a] ± (220.60)	721.76[b] ± (187.60)	1904.62[c] ± (250.90)	1137.98[d] ± (215.70)	0.000

P value ≤ 0.05; mean values with different letters have statistically significant differences.

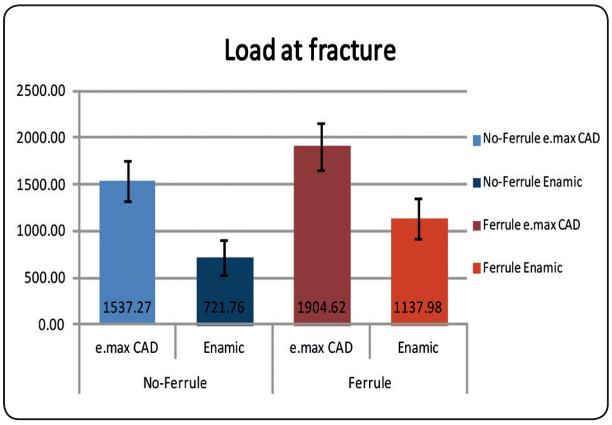

Fig. (3) Histogram of load at failure mean values (N) with standard deviation bars for the tested subgroups.

Finite element analysis (FEA) evaluation of different models at load of failure:

Table 4 and Figure 4 show the maximum von Mises stresses (in MPa) generated in the components of the four models and their distribution. Results of FEA showed that in all models maximum von Mises stresses generated in the tooth structure exceeded the maximum tensile strength of dentin indicating the occurrence of collapse in the tooth structure. The stresses generated in dentin restored with Enamic regardless of design were higher than the tensile strength of dentin by about 10%, while dentin restored with e.max CAD with No-Ferrule endocrown was stressed 29% higher than its tensile strength. Under e.max CAD with Ferrule endocrown, the dentin was stressed 61% higher than its tensile strength. The stresses generated in the luting cement used to cement Ferrule endocrowns whether e.max CAD or Enamic were 80% and 18% higher than the tensile strength of the cement, respectively. On the other hand, the stresses generated in the luting cement used to cement endocrowns with No-Ferrule whether e.max CAD or Enamic were lower than the tensile strength of the cement by 28% and 64%, respectively. Endocrown with Ferrule and made from e.max CAD was subjected to maximum von Mises stresses 8% higher than the tensile strength of its material. In contrary, endocrowns with No-Ferrule and made from e.max CAD and Enamic, in addition to that made from Enamic with Ferrule showed maximum von Mises stresses lower than the tensile strengths of their materials by 33%, 70% and 39% respectively. The highest stresses generated under Ferrule design were located at the crest of the ferrule in the dentin and cement. However, the highest stresses generated in tooth restored with e.max CAD with No-Ferrule design were located at the trunk area, while that restored with Enamic with No-Ferrule design showed highest stresses at the butt joint. Among all groups, the model of Enamic endocrown with No-Ferrule showed the best stress distribution within its all components.

TABLE (4) Maximum von Mises stresses (in MPa) generated in the components of the four investigated models.

	No-Ferrule		Ferrule	
	e-max CAD	Enamic	e-max CAD	Enamic
Endocrown	29.141	13.731	46.832	27.257
Resin cement	35.725	18.050	90.002	59.087
Prepared tooth	68.808	59.224	85.927	58.566

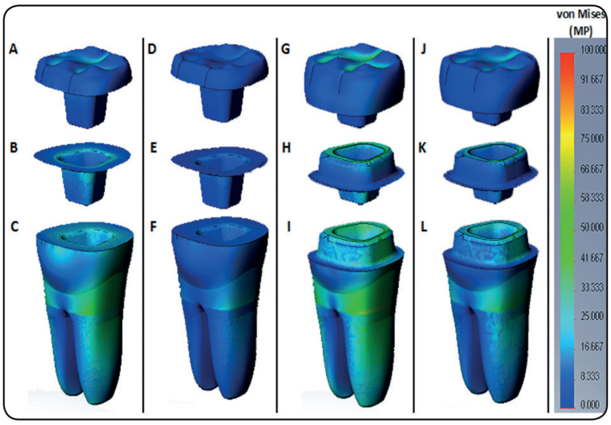

Fig. (4) Stress distribution (in MPa) in the assemblies of the four groups. A, B and C represent No-Ferrule design for e.max CAD endocrown, resin cement and prepared molar respectively. D, E and F represent No-Ferrule design for Enamic endocrown, resin cement and prepared molar respectively. G, H, and I represent Ferrule design for e.max CAD endocrown, resin cement and prepared molar respectively. J, K and L represent Ferrule design for Enamic endocrown, resin cement and prepared molar respectively.

TABLE (5) The calculated Weibull modulus (***m***) and the characteristic strength ($\boldsymbol{\sigma_0}$) for the tested models.

	No-Ferrule		Ferrule	
	e-max CAD	Enamic	e-max CAD	Enamic
Weibull modulus (m)	7.47	4.1	8.18	5.32
Characteristic strength (σ_0)	1634.1	796.84	2014.42	1236.31

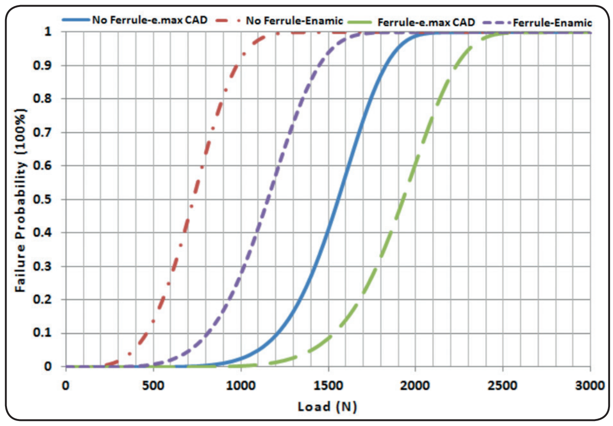

Fig. (5) A graph showing failure probability vs. load curves of the four tested groups.

Weibull risk of failure:

Table 5 shows the Weibull modulus (m) which is the shape parameter of the subgroups models and their characteristic strength (σ_0) which represents the stresses that would cause failure of 63.2% of assimblies.

The failure probabilities of the four subgroups are presented in Figure 5. Enamic endocrowns with No-Ferrule assembly showed the highest failure probability curve followed by curves of Enamic with Ferrule and e.max CAD with No-Ferrule assemblies respectively. The least failure probability curve was that representing the e.max CAD with Ferrule assembly.

DISCUSSION

Intraradicular posts have been widely suggested as the classical line of treatment for restoration of endodontically treated molars, especially in the presence of gross tissue loss, not only to retain the crown but also to recover the lost mechanical properties of the tooth.[7] However, it is largely proved today that intraradicular posts do not reinforce the tooth and may even contribute to its weakness.[50,51] The new achievements in the adhesive systems and techniques as well as the growing concept of tooth conservation using minimal invasive procedures had developed the ‘endocrown’ as a new treatment modality for devitalized teeth.[17,21,23,24]

The use of endocrowns allows for a more conservative approach in the treatment of ETT, preserving tooth tissues and allowing re-intervention in case of endodontic failure.[52] Furthermore, the conservation of peripheral enamel maintains the possibility to adhesively bond margins of the restoration. This is known to have a favorable effect on the restoration marginal stability keeping those margins away from the periodontium and hence maintaining its health and hygiene.[53]

The success of this type of restorations depends to a great extent on the material selected for constructing endocrowns which should be capable of being adhesively bonded to the remaining devitalized tooth structure.[17] In addition; the selected material should withstand the physiological load applied in the posterior region. The fracture resistance of ETT is one of the most important factors when selecting the restorative material especially when there is a considerable amount of lost tooth structure.

Based on these concepts; two restorative materials were selected for endocrowns construction in the present study; e.max CAD and Vita Enamic. E.max CAD is a lithium disilicate (LD) based glass ceramic. With the presence of silicate glass within its matrix; superior adhesive bonding is expected after etching and sialinization. Furthermore, Vita Enamic is a polymer infiltrated ceramic network (PICN) which contains 75 vol% ceramic-matrix and 25 vol% polymer.[54,55] The ceramic matrix is mainly leucite-based silicate glass while the polymer component is composed of urethane dimethacrylate (UDMA) and triethylene glycol dimethacrylate (TEGDMA).[33] Like LD, PICN is an etchable ceramic with a reliable durable bonding. It has been claimed that the existence of polymer in its composition could reduce brittle fracture in comparison to pure ceramic materials.[19] However, its load bearing capacity under repeatable chewing process is still unclear.

Accordingly, for both materials used, the surface treatments proposed were indicated for cementation of etchable ceramics; hydrofluoric acid etching followed by silane application.[56,57] The glass content of these ceramics suffers a selective dissolution when exposed to hydrofluoric acid, increasing the surface roughness and promoting a better micromechanical interlocking with the resin cement.[58]

Understanding the mechanical properties of dental materials is important to estimate their clinical performance. Traditional laboratory testing involves static loading of test specimens in a universal testing machine until failure.[59] While this static loading of a restorative material is important,[55] as they can provide information about material strength, estimate failure risk, or compare material variants, yet it is still inadequate to predict the long-term performance of dental restorations during service in the complex oral conditions.[59] Clinically, mechanical failure of dental restorations usually occurs after many years in service, indicating a fatigue failure rather than acute overload.[60] Damage accumulates from cyclic contacts between maxillary and mandibular teeth and finally limits the survival probability and lifetime of the restorations.[61] The longevity of dental restorations under cyclic loading is more clinically relevant, as fatigue failure usually occurs in subcritical loads without any previous warning for the upcoming failure.

There is still inconsistency in fatigue protocols adopted by different authors to assess different restorations. Studies fail to agree on specific settings for the multiple parameters that should be applied to achieve the closest clinical simulation. In the oral cavity, failure by fatigue is influenced by many variables including the magnitude of the masticatory load, the opposing material, the condition of the supporting tooth structure, the periodontium condition, the wet environment, the fluctuation in temperature, and the mouth opening distance.[62] Taking all these variables into consideration to test failure by fatigue is quite difficult. Slight variation in any of these factors changes the testing parameters significantly and poses difficulty in comparing results among different studies. Researches usually apply cyclic loading for a particular number of cycles representing clinical service for a specific number of years. It has been agreed that 250,000 cycles represent mechanically 1 year in service.[63,64] In the present study, a fatigue procedure composed of cyclic loading (49N, 120,000 cycle) representing 6 months in service, associated with a thermocycling procedure (5^{O}C-55^{O}C) in a chewing simulator was applied to the tested samples prior to a static load to fracture test. Although this testing procedure does not precisely represent the fatigue failure of a dental restoration, it comprises the cyclic load and temperature fluctuation in a moist environment aiming at resembling the clinical situation as much as possible.[65]

In the present study two preparation designs were compared; No-Ferrule and Ferrule designs. The No-Ferrule design includes butt joint preparation. In contrary, the Ferrule design, where a 2.5mm ferrule was included in the preparation starting 1mm coronal to the CEJ. Fracture resistance results showed that Ferrule design had statistically significant higher values compared to the other design, in both tested materials. Therefore, the null hypothesis was rejected.

The “ferrule effect” is a longstanding, foundation principle for the restoration of ETT that have suffered advanced structure loss yet still have sufficient tissue for ferrule preparation.[66] Jotkowitz and Samet, 2010 [67] reported that a ferrule being a 360° collar of the crown surrounding the parallel walls of the dentin extending coronal to the shoulder of the preparation, it provides protection against fracture of the tooth, by reducing developed stresses. However, at the failure loads, FEA revealed that stresses generated in ferrule design were higher than those in the no ferrule design; hence its ability to protect the underlying tooth structure is probably due to its strengthening effect of the teeth against functional, wedging, and lateral forces.[68] The majority of studies support the effectiveness of using a ferrule in protecting ETT against fracture by reinforcing the tooth at its external surface.[69–76] Endocrowns with Ferrule design would mask small fractures of dentin and cement beneath till stresses reaches higher levels in other areas in the tooth not protected by the ferrule leading to sudden collapse of the whole structure. This was clearly detected in FEA where the stresses generated in dentin and cement under endocrowns with ferrule markedly exceeded their tensile strength before failure of the structure. This come in agreement with previous studies which found that ferrule strengthen non-vital teeth by reinforcing them at their external surfaces and encircling the circumference of the preparation.[70–74] Although stresses in Enamic endocrown with Ferrule did not reach its tensile strength, however mechanical test at this load value showed fracture of the assembly. This could be due to generation of stresses of 58.6MPa at the molar trunk leading to massive fracture of the tooth with its fragmentation which is not assumed by the FEA program. This fragmentation reduced the area of support under the endocrown elevating the practical values of stresses above the material tensile stress leading to fracture of the endocrown as well. This also was detected in endocrowns with no ferrule design of both materials.

Isidor et al [77] and Zicaria et al [78] documented the ferrule effect in increasing the fracture resistance of ETT after cyclic fatigue procedure conducted in a chewing simulator. Both studies emphasized the effect of the ferrule which was more prominent than the restorative procedure in increasing the fracture resistance of ETT.

Regarding the material, the results of the present study revealed a significant difference between fracture resistance of ETT restored using both materials; e.max CAD endocrowns recorded higher failure load values within the two designs tested compared to Enamic endocrowns. The null hypothesis was thus rejected. It was found by FEA that Enamic material generated stresses in the models much lower than those generated by e.max CAD. Thanks to polymer network, Enamic is more resilient and has high ability of absorbing forces and stopping crack formation compared to lithium disilicate based ceramics.[79,80]

In complex multilayered restorations, such as cemented ceramic restorations, several factors contribute to the mechanical behavior of the restoration/tooth system. The intrinsic strength of each component of the system (i.e. tooth, adhesive system, luting cement layer, and restoration), the thickness of the restorative material, the ratios of elastic moduli between the restorative material, the luting cement and dentin, and finally the quality of the adhesive interface between these layers in terms of bond strength and presence of micro- or nanoleakage, are all factors that play a role in the behavior of such restorations.[59] In the present study, it seemed that in most cases the strength of the teeth and cement was the dominant factor that influenced the failure load of the endocrowns. Hence most endocrowns did not fail till failure had occurred first in the underlying structures as proved by FEA.

The mechanical properties of polymer infiltrated ceramic network (PICN) based materials were described to be closer to natural dentin and enamel.[81,82] The hardness and elastic modulus of these materials are closer to those of the dental tissues values making them good candidates for restoring posterior areas.[57] Furthermore, Ausiello [83] indicated that the elastic modulus of adhesive cements is very similar to the PICN value, reducing stress arising at the interfaces. In addition, it had been suggested that high elastic modulus of the restorations is the primary factor to minimize the stress concentration at the coronal structure.[10] So e.max CAD was expected to produce better stress distribution with lower stress concentration than did Enamic, however, the opposite was happened which might be due to presence of polymeric material in its structure that is more resilient and implies higher capacity of load energy dissipation.[84]

Some studies[10,25,85] reported significantly higher mean fracture resistance for hybrid ceramic endocrowns compared to e.max CAD and feldspathic endocrowns. These studies explained these results on the basis of the modulus of elasticity of the resin-ceramics being similar to dentin. The modulus of elasticity influences the susceptibility to fracture of a cemented ceramic restoration since materials with more compatible elastic moduli tend to bend under load and transmit less stresses to the underlying structures, while rigid materials with different elastic moduli, such as lithium disilicate, are less resilient that might undergo catastrophic failures.[86,87] These results contradict the results obtained in the present study; however, they were obtained using impact fracture testing procedure rather than thermomechanical fatigue procedure used in the present study.

This contradiction suggests that although the modulus of elasticity of hybrid ceramics improved the fracture resistance of the restoration under impact loading according to previous studies; [10,25,85] the application of a thermomechanical fatigue protocol might have caused deterioration of the strength properties of these materials. Consequently, the fracture resistance predominantly depended on the intrinsic mechanical behavior of the material itself thus e.max CAD showed higher failure load values than Vita Enamic. Albero et al [47] while assessing mechanical properties of Vita Enamic, found that e.max CAD recorded significantly higher failure load values compared to Enamic. It can be summarized that PICN materials are weaker than lithium disilicate ceramic; the former may fail at lower stress level, yet they are more resilient that they can transmit lower stresses to the underlying structures.

In addition, Homaei et al [88] when compared the static and fatigue mechanical behavior of lithium disilicate based and hybrid ceramic; found that fatigue resistance of lithium disilicate based ceramic was higher than that of PICN (Enamic). Unlike ductile materials, a crack does not initiate naturally in brittle ceramic materials. Typically, it is initiated from any pre-existing defects, and when in tension, they cause localized stress concentrations when they are loaded more than a bearable level.[89,90] Failure may be initiated from any surface void, weak point of microstructure, like polymer in PICN, or some intrinsic flaws.[89] Accordingly, the presence of polymer in the PICN composition presents a weak point that may cause deterioration of the strength after thermomechanical fatigue.

Another explanation of this result is based on the bonding capacity of each restorative material to the adhesive resin cement and the susceptibility of this bond to the fatigue procedure employed. Strong adhesive bond between the restoration and tooth structure ensures a homogenous distribution of stresses leading to a superior mechanical performance of the restoration. Lithium disilicate based ceramic exhibit a high bond strength to adhesive resin cements as stated in previous studies.[91,92] On the other hand, the resin component of the Enamic (PICN) is expected to promote a superior adhesive bond with resin cements resulting in better stress distribution.[25] However, after thermomechanical fatigue; the change in temperature and exposure of the samples to water poses a challenge of this bond causing its deterioration.[58] The aging protocol decreases the adhesion due to the small molecular size and high molar concentration of the water, which can penetrate small spaces between polymer chains or functional groups, resulting in a decreased thermal stability of the polymer and causing its plasticization.[16] Thus, it is possible that the polymer present in the (PICN) although promoted the adhesive bond initially; it could not withstand moisture and temperature variations and deteriorated accordingly.

The use of human teeth in this study has increased variations among samples with difficult standardization. Although effort was made to select molars with approximate dimensions, the anatomy and size of the pulp chamber of each molar was difficult to standardize. Yet it was essential to use natural teeth to simulate clinical situation.

The Weibull risk of failure is frequently used to calculate the fracture probability of brittle structures and material, furthermore, it is a method to predict probability of failure at a given level of loading.[26] Many previous studies have studied the average biting force at the first molar region and they found great variations between 345.3N to 774.7N.[93,94] At load values of 774.7N, Weibull risk of failure revealed that about 8% of Enamic with ferrule assembly would fail and it would be as high as 55% for Enamic with No-Ferrule assembly at the same load value. Teeth restored with e.max CAD endocrowns showed 100% survival rate at the same load. At load level of 345.3N, only about 3% of Enamic with No-Ferrule assembly would fail, while others would not. Hence, both materials with two design modalities would be used safely in patients with low masticatory forces, while those with higher forces, e.max CAD would perform better than Enamic especially if No-Ferrule design would be used.

CONCLUSIONS

Within the limitation of this study, the following could be concluded:

1. Including a ferrule within the preparation design of endocrowns improves the fracture resistance of ETT.
2. Constructing endocrowns using lithium disilicate based ceramics leads to superior fracture resistance of ETT, compared to using hybrid ceramics.
3. In patients with low masticatory forces, both materials with both designs would work safely.

Conflict of interest:

The authors declare no conflict of interest to disclose.

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