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The influence of ferrule height and substance loss on the fracture resistance of endodontically treated premolars - An in-vitro study

[Der Einfluss der Höhe der Ferrule und Substanzverlust auf die Bruchfestigkeit endodontisch behandelter Prämolaren: Eine In-vitro-Studie]

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ABBREVIATIONS

ANOVA	analysis of variance
CEJ	cemento-enamel junction
ETT	endodontically treated teeth
FDPs	fixed dental prostheses
FPs	fiber posts
GFPs	glass fiber posts
GPa	gigapascal
N	newton
RCT	root canal treatment
RDPs	removable dental prostheses
SD	standard deviation

1. INTRODUCTION

The restoration of the endodontically treated teeth (ETT) has been evaluated and discussed widely in the dental literature. Despite the large number of in-vitro and in-vivo investigations, however, there is still much confusion regarding their ideal treatment.

ETT are a unique subset of teeth requiring restoration because of several factors. Firstly, it was thought that the dentin of ETT differed significantly from vital dentin [45]. However, more current research casts doubt on this assumption [49]. Secondly, a percentage of structural integrity is lost because of the endodontic access preparation [63, 84]. This loss clearly has a negative effect on the fracture resistance of ETT. Thirdly, the neurosensory feedback mechanism is impaired with the removal of the pulpal tissue, which may result in decreased sensory protection of ETT during mastication [83]. The most important factor which is affecting the prognosis of ETT is the amount of remaining coronal tooth structure and ferrule height before the final restoration [63, 117]. This factor is much more important than others that are reported, such as post material, post design (diameter and length), cement type and core materials [54, 114].

1.1. REVIEW OF LITERATURE

ETT should have a good prognosis to resume full function and serve satisfactorily as abutment teeth for crowns, fixed dental prostheses (FDPs) or removable dental prostheses (RDPs). Several studies have suggested that the dentin in non-vital ETT is different from dentin in vital teeth [24, 45, 85]. It was thought that the dentin in ETT is more brittle because of water loss and loss of collagen. However, other studies contradicted this view. Sedgley and Messer [95] studied the biomechanical properties such as punch shear strength, toughness, hardness, and load to fracture of ETT (mean time since endodontic treatment: 10.1 yr.) and compared them to their contralateral vital pairs. Their findings did not support the conclusion that ETT are more brittle. Cheron *et al.* [26] studied the nanomechanical changes of the ETT and compared them with vital teeth. They found that root canal treatment does not result in nanomechanical changes to radicular intertubular dentin. Huang *et al.* [49] compared the physical and mechanical properties of dentin specimens from teeth with and without endodontic treatment at different levels of hydration. They concluded that neither dehydration nor endodontic treatment caused degradation of the physical or mechanical properties of dentin.

1.2. Restoration of ETT

The restoration of ETT is one of the most challenging situations of the dentist's clinical practice and has long been a concern of dentistry, because it involves procedures related to several areas, such as Endodontics, Operative Dentistry, and Prosthetics. Restoration of ETT has been evaluated and discussed widely in the dental literature and there are a variety of materials and techniques advocated for restoring pulpless teeth. Restorative treatment may vary, ranging from a relatively small direct restoration to more complex indirect restorations involving the placement of an intraradicular post and core and the indirect

restoration itself. Primarily, preservation of tooth tissue, presence of a ferrule effect, and adhesion are regarded as the most effective conditions for long-term success of the restorative procedure [33, 34, 36, 94, 107]. The treatment of the ETT should include the decision of whether or not root posts should be used. The use of posts, however, does not increase the fracture resistance significantly. This has been shown in several comparative in-vitro studies [18, 44, 66], but the use of posts serves to improve retention of the core. The decision regarding post placement should be made based on the position of the tooth in the arch [81, 99], the amount of coronal remaining tooth structure [63], and the functional requirements of the tooth [42], e.g. if a tooth would be used as an abutment for removable or fixed dental prostheses.

1.2.1. Anterior teeth

Anterior teeth are subjected to shearing forces and are usually restored with posts [1]. When there is no functional or aesthetic requirement for a full-coverage restoration, a post is not indicated. If a full-coverage restoration is chosen, however, the decision to place a post is dictated by the amount of coronal remaining tooth structure after the crown preparation is completed and the functional requirements of the restored tooth [44, 99].

1.2.2. Premolar teeth

Premolars are subjected to vertical forces and shear forces if there is unilateral group guidance. A decision regarding post placement is made based mainly on the remaining coronal tooth structure [63], and the functional requirements of the tooth [94]. There might be also considerable shear forces in premolars if there is unilateral group guidance.

1.2.3. Molar teeth

Posterior molar teeth are subjected to vertical forces and posts are rarely required when there is no large percentage of coronal tooth structure missing

[12, 92]. When a decision regarding post placement is taken because of lack of adequate remaining coronal tooth structure, it should be placed usually in the largest root canal [94], i.e. the palatal canal in the maxillary molar and the distal canal in the mandibular molar.

1.3. Factors affecting the fracture strength of ETT

1.3.1. The amount of remaining walls

The amount of remaining tooth structure is probably the most important predictor of clinical success and to raise the fracture strength of ETT [7]. In terms of failure loads the height of the residual dentin was reported to be more important than the post system used. Other in-vivo and in-vitro studies [2, 19, 29, 106] have shown the importance of height and location of the remaining tooth structure for the mechanical properties of restored ETT. Mangold and Kern [63] reported an improved resistance to fracture when more residual dentin walls are available. They stated that the presence of at least 2 residual dentin walls is important to avoid using intraradicular posts but they did not indicate the effect of varying ferrule height in their study.

1.3.2. The ferrule effect

The ferrule (Fig. 1) is an encircling band of the crown around the coronal surface of the tooth [98], more precisely, parallel walls of dentin extending coronally from the crown margin provide a “ferrule,” which after being encircled by a crown provides a protective effect by reducing stresses within a tooth called the “ferrule effect” [102]. An adequate ferrule is necessary for a successful post-retained restoration. Several studies reported an improved resistance to fracture of ETT when an encircling ferrule was used with a post [19, 31, 46, 118]. The ferrule can reduce significantly the incidence of fractures in non-vital teeth by reinforcing the tooth at its external surface and redistributing applied forces which concentrate at the narrowest point around

the circumference of the tooth [100]. In addition, it helps to maintain the integrity of the cement seal of the crown [60].

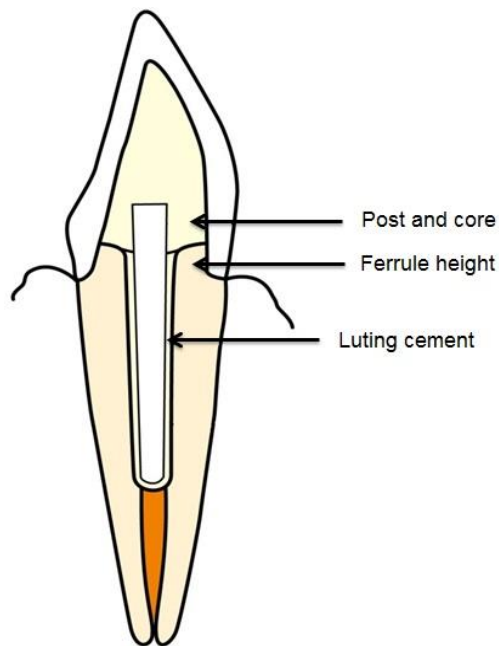


Fig. 1 The ferrule effect.

1.3.3. Core materials

The presence of significant coronal tooth structure loss requires abutment build-up around a post [89]. Several core materials are available such as: amalgam, composite resins, glass ionomer cements, alloys and ceramics. The elastic moduli of some commonly used core materials are as follows: 17-21 GPa (composite resin), 28-59 GPa (amalgam), 218-224 GPa (cobalt-chromium alloy), and 90-95 GPa (Type IV gold alloy) [28]. Depending on the post material being used and its physical properties, the post and core can absorb occlusal and functional stresses that are applied to the bonded post/crown complex and redirect them along the long axis of the remaining root which lead to increase fracture strength of ETT [27, 91]. The stiffer core materials increase the cervical stress and diminish the apical stress [116]. Several laboratory and clinical studies supported the use of composite materials for building up the

core portion [47, 82, 108]. Restorations with fiber posts (FPs) and composite resin cores were found to be more effective than amalgam in preventing fracture of ETT [64]. With the evolution of the dentin bonding technology [57], it may be possible to obtain an integrated tooth-post-core bonded restoration, instead of an assemblage of heterogeneous materials (i.e., post [metal], cement [zinc phosphate], and core [metal, amalgam, or composite resin]).

1.3.4. Post design

In the past a post was generally placed in an attempt to strengthen the tooth. However, as dentin has to be sacrificed, especially when a metal post is utilized, a post does not strengthen the root, but serves solely to improve retention of the core. The purpose of a post and core together is to reinforce the remaining coronal tooth structure and to replace missing coronal tooth structure [86]. Although some studies indicated that a post strengthens a tooth [56, 111], but most studies suggested that this is not the case [18, 44, 66, 87]. In a study where the reinforcement effect of cast posts and pins was examined, it was found that the ETT without posts which served as control group were twice as resistant to fracture as the teeth treated with posts or pin-retained cores [61].

1.3.4.1. Post shape

Many commercially available prefabricated posts exist. For example, the axial form is either tapered or parallel, and the surface can be smooth, serrated with or without vents, or threaded using taps or self-threading. Parallel-sided posts are more retentive than tapered posts [110], and they distribute stress more uniformly along their length during function which may lead to lower fracture rates of ETT than do tapered posts [97]. Threaded posts are more retentive but can predispose the root to fracture in ETT [40]. Screws have a higher incidence of root fractures in ETT and their survival rate may be significantly reduced [30].

1.3.4.2. Post length

There are many guidelines in the literature concerning the length of the post. Some studies have suggested that the post length should be equal to a certain amount of the root, e.g. half the length of the root [17, 52], two thirds of the root length [58] or at least half way between the apex of the root and the alveolar crest of supporting bone [79, 104]. The length of the post affects stress distribution in the root of ETT which affects its resistance to fracture [50]. In-vitro biomechanical studies also have suggested that better stress distribution occurred with longer posts [48]. An increased post length was associated with an improved fracture strength of ETT [111]. Generally, it has been shown that the post length is less important for fracture resistance of ETT than the ferrule effect [50].

1.3.4.3. Post diameter

One of the controversial factors in fracture resistance of dental roots is the diameter of the endodontic posts. A post requires an adequate diameter to achieve favorable physical and mechanical characteristics without the risk of fracture [11]. However, increasing the diameter of the post adds to its strength but at expenses of the sound tooth structure, thus leading to weakening of the whole entity of ETT [73]. The post space should be prepared conservatively and at least 1.0 mm thickness of sound dentinal wall should remain around the post [11]. On the other hand, an increase in the post's width will increase the risk of root fracture [43, 101]. Robbin [86] recommended that the diameter should be "as small as possible" to increase the fracture resistance of ETT by minimizing the loss of the tooth structure.

1.3.4.4. Post materials

Posts can be divided into two large groups: custom-made and pre-fabricated posts. The custom-made cast posts have been used for many years

with good success [22, 30]. They exhibit some features unfavorable to tooth remnant preservation, such as irregular stress dissipation and stress concentration at apical area which may lead to root fracture of ETT [51]. On the other hand, prefabricated non-metal posts save time and can provide satisfactory results [105, 109]. They provide retention to a core portion [98] which is directly built up onto the post with a composite resin. Accordingly, it might be assumed that FPs offer additional advantages such as that their modulus of elasticity is similar to dentin (Fig. 2) which allows reducing stress transmission to root canal walls and increasing the fracture strength of ETT [8]. It has been also suggested that the failure with FPs is less likely to include irreparable root fracture of ETT than with metal posts [3, 27].

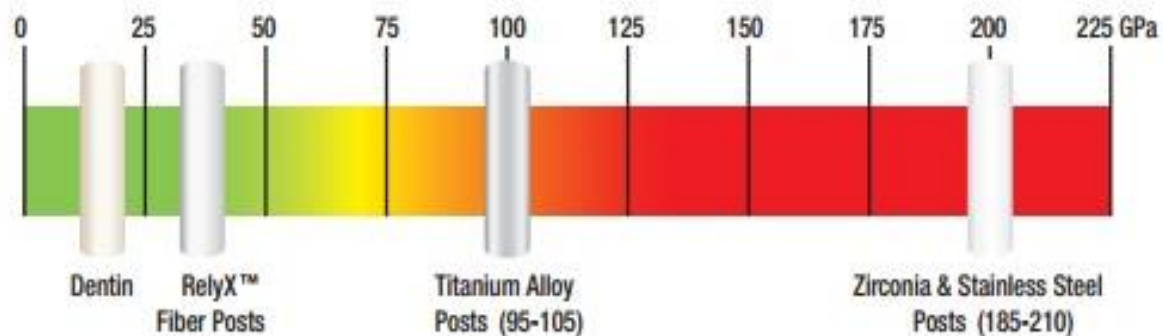


Fig. 2: Elasticity modulus (GPa) of dentin and post materials (3M ESPE internal data).

1.4. Bonding of posts

Bonding of posts to radicular dentin is one of the most challenging situations faced by the clinician. Several cements, such as zinc phosphate, glass ionomer, modified glass-ionomer and resin cements, can be used to cement posts systems to dentin walls [14, 37, 53, 101, 113]. Zinc phosphate cement has been widely used in FDPs due to its easy handling properties and satisfactory long-term clinical results [53]. It bonds by mechanical interlocking to the dentin and the prosthetic materials [6]. Glass-ionomer cements have also been used in luting

posts. Their advantages are ease of use, good bonding to tooth structure, releasing significant amounts of fluoride, and anticariogenic properties [28]. Several studies have reported higher resistance to fatigue for resin cements compared to brittle zinc phosphate cements and glass ionomer cement [4, 10, 55, 65, 68]. Resin cements are especially recommended when luting FPs and ceramic posts [65]. Posts form a bonded unit between root and coronal dentin, adhesive systems, resin cements, and composite build-up (Monoblock) which lead to raising the fracture strength of ETT [115].

In clinical studies, it has been shown that failure of adhesively luted FPs often occurs due to debonding of the post [37, 71].

1.4.1. Luting cements

Since the 1980s, resin cements have been preferred to conventional zinc-phosphate cements for post luting, because they have been shown to increase the retention of the post [88] and the overall resistance against fracture of ETT [76]. Due to the low elastic modulus of the adhesive cement, it may act as a shock absorber, thus decreasing the risk of fracture of ETT [68]. Moreover, the elastic modulus of composite cements is in the same range of both FPs and dentine. The resultant homogeneous biomechanical unit allows a more uniform stress distribution, which better preserves the weakened tooth structure in ETT [77].

1.5. AIM OF THE STUDY

The review of the literature showed that the increase in either ferrule height *or* the number of remaining walls of weakened ETT may increase the teeth resistance to fracture. However, little is known about the combined effect of both factors, i.e. remaining walls and ferrule height, in terms of reinforcement of weakened ETT. Therefore, the aim of this study was to evaluate the fracture resistance of endodontically treated premolars restored with glass-fiber posts when different ferrule heights and varying degrees of substance loss were incorporated.

The null hypothesis of the study is that neither the ferrule height nor the amount of residual coronal dentin would affect the fracture resistance of crowned premolars.

2. MATERIALS AND METHODS

2.1. Test groups

Materials used in the restorative procedures are listed in Table 1. After informed consent was obtained according to the regulations of the ethical committee of the Christian-Albrechts University at Kiel, eighty recently extracted caries-free lower first premolars were selected, which removed for periodontal or orthodontics reasons, and stored in 0.1% thymol solution (Caelo, Hilden, Germany). The teeth were cleaned with a hand scaler and stored at room temperature during the study. Endodontic access cavities were prepared using a water cooled air turbine handpiece. The teeth were endodontically prepared using the step-back technique to an ISO size 50 (K-files; Dentsply De Trey, Constance, Germany), irrigated with 3% sodium hypochlorite solution (Hedinger, Stuttgart, Germany) and dried with paper points (Coltene/Whaledent Inc, Langenau, Germany).

Table 1- Materials used for restorative procedures

Material	Company	Batch number
ER Dentin Post	Brasseler, Lemgo, Germany	676303
Clearfil Core	Kuraray, Osaka, Japan	041523
Permadyne Penta H	3M/Espe, Seefeld, Germany	H 434544, L 422524
Panavia 21	Kuraray, Osaka, Japan	041344
Ketac Cem Maxicap	3M/Espe , Seefeld, Germany	347837
Cobalt-chromium alloy	Wirobond C, Bego, Bremen, Germany	3533

During root canal preparation, the working length was set at 1 mm short of the apical foramen. Each canal was obturated using the lateral condensation method with gutta-percha points (Coltene/Whaledent Inc, Langenau, Germany)

and sealed with an eugenol-free epoxyamine resin sealer (AH Plus; Dentsply De Trey, Constance, Germany) [21, 70]. The coronal aspect of the gutta-percha was removed with a heated probe and the endodontic access cavities were filled with a temporary filling material. The teeth roots were embedded into brass tubes, using an auto-polymerizing resin (Technovit 4000; Heraeus Kulzer, Wehrheim, Germany) up to 2 mm apical to the cemento-enamel junction (CEJ) and oriented their long axes perpendicular to the horizontal using a custom-made surveyor (Fig. 3). The ETT received 0.8 mm shoulder finish lines which were mesial and distal 1 mm more coronal than the facial and lingual surfaces and which were cervical 1 mm to the cemento-enamel junction (CEJ). Burs were replaced after 8 preparations, in order to ensure high cutting efficacy. For teeth preparations, diamond rotary cutting instruments under copious air-water cooling (Komet Dental, Lemgo, Germany) were used in a high-speed handpiece mounted on a custom-made parallelometer to standardize the preparation for all specimens.



Fig. 3: Tooth preparation using a custom-made surveyor.

The teeth were assigned randomly to 5 groups of 16 teeth each according to the ferrule height (Figs. 4&5). The properties of the specimens included in each group were as follows: group A (control group): Specimens without circumferential ferrule; group B: Circumferential ferrule 0.5 mm above the

finish line; group C: Circumferential ferrule 1 mm above the finish line; group D: Circumferential ferrule 1.5 mm above the finish line; and group E: Circumferential ferrule 2 mm above the finish line.

Eight specimens per subgroup were chosen because in the masticatory simulator 8 specimens can be loaded at a time.

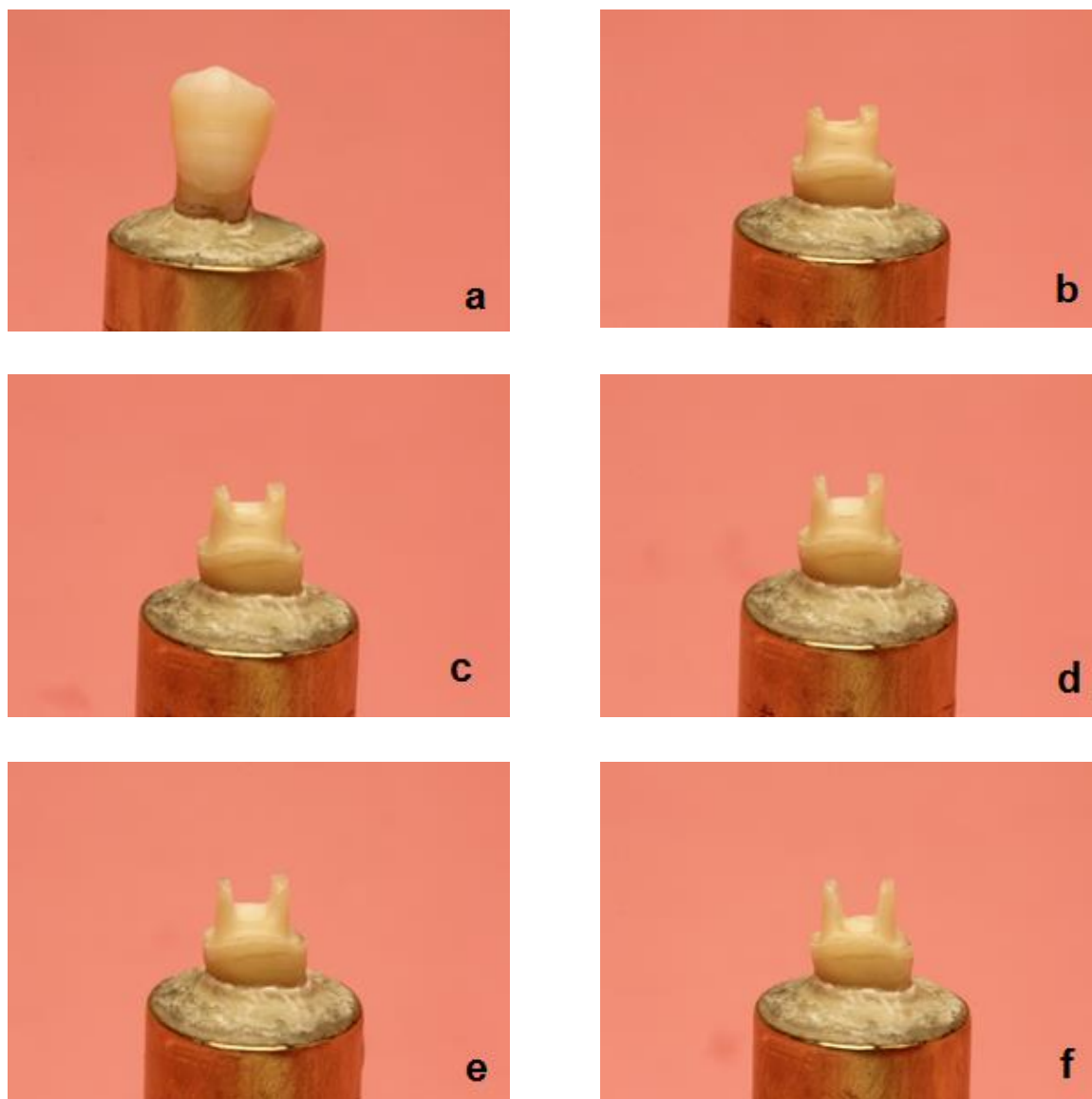


Fig. 4: Prepared specimens with two dentinal wall and different ferrule height: a) sound specimen (without any preparation), b) with 2 mm ferrule height, c) with 1.5 mm ferrule height, d) with 1 mm ferrule height, e) with 0.5 mm ferrule height, f) without ferrule.

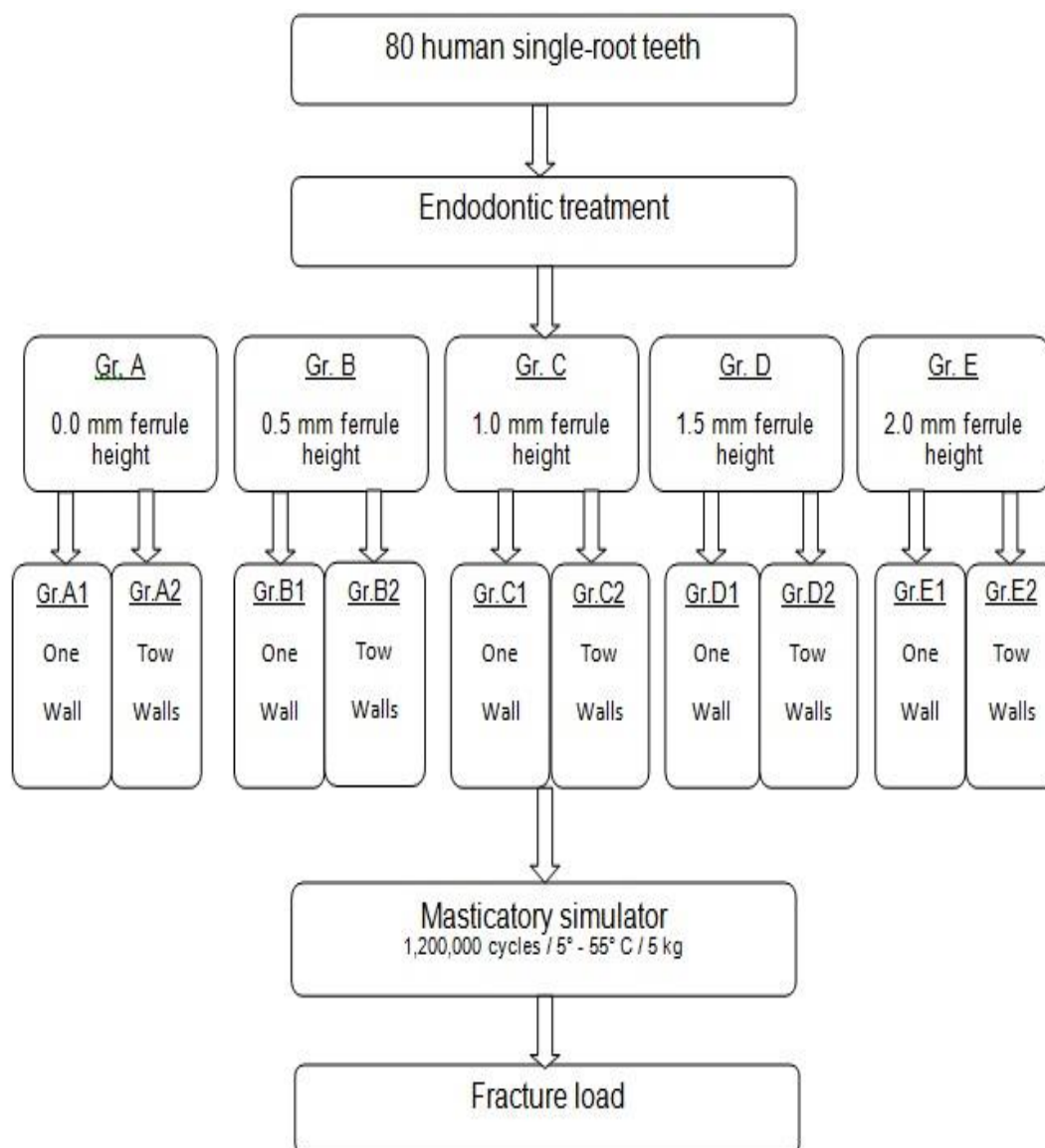


Fig. 5: Flow chart of study design.

For all teeth, post spaces were accomplished with a tapered drill (ER-post kit; Brasseler, Lemgo, Germany) of ISO size 90 (Fig. 6) to achieve an intraradicular post length of 7.5 mm. The coronal opening of the post space were enlarged in a facio-lingual direction to a width of 3 mm and depth of 2 mm to resist rotation and to standardize the coronal openings and the thickness of residual coronal walls. The walls of the post preparation were roughened using a diamond-coated hand instrument 3 times (ER Post Systems; Brasseler, Lemgo, Germany) [16].

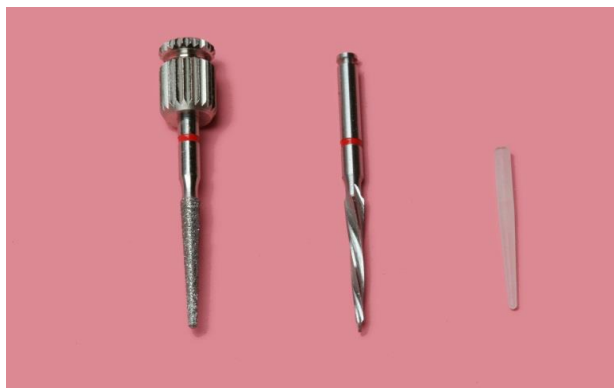


Fig. 6: ER-Post-System with ER-Dentin-Post (Komet, Brasseler, Lemgo, Germany).

The GFPs (Fig. 7) (Komet ER DentinPost; ISO size 90, Brasseler, Lemgo, Germany) were airborne-particle abraded for 5 seconds at a distance of 30 mm with 50 μm alumina particles (Heraeus Kulzer, Wehrheim, Germany) at 0.25 MPa and cleaned ultrasonically in 96% isopropanol (German Federal Monopoly Administration for Spirits, Hamburg, Germany) for 3 minutes [15].



Fig. 7: The GFP inside the root canal.

The post spaces were then irrigated with a 3% sodium hypochlorite solution and dried with paper points, followed by irrigation with 70% ethanol (German Federal Monopoly Administration for Spirits, Hamburg, Germany) and drying with paper points. The irrigation with 70% ethanol, simulating the clinical situation, was used to disinfect and dry the canals. The posts were luted with adhesive composite-resin cement (Panavia 21; Kuraray Medical, Osaka,

Japan) after conditioning the dentin with the system's autopolymerizing primer (ED-Primer; Kuraray, Osaka, Japan) for 60 seconds. The resin cements were mixed and applied according to the manufacturer's instructions (Fig. 8), equal amounts of the catalyst and the universal pastes were dispensed by turning the syringe of each paste one complete turn. The dispensed pastes were then mixed for 20-30 seconds using a plastic spatula. Excess luting resin was used to coat the coronal portion of the post.



Fig. 8: Panavia 21 resin cement.

An auto-polymerizing composite resin (Clearfil Core; Kuraray Medical, Osaka, Japan) was applied as the core material. After complete polymerization of the resin, the core was prepared to the required dimensions (Fig. 9).

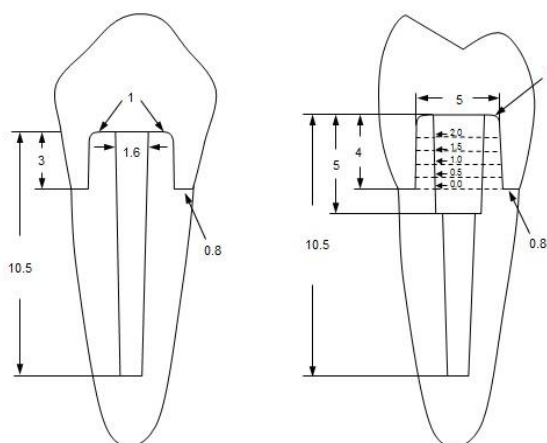


Fig. 9: Dimensions of preparation, restoration and ferrule height (in mm).

2.2. Cast crown fabrication

Impressions (Fig. 10) of the prepared specimens were made with a polyether impression material (Permadyne Penta H; 3M/Espe, Seefeld, Germany). After 30 minutes, the impressions were poured in type IV stone (Fig. 11) (GC Fujirock EP, Leuven, Belgium).

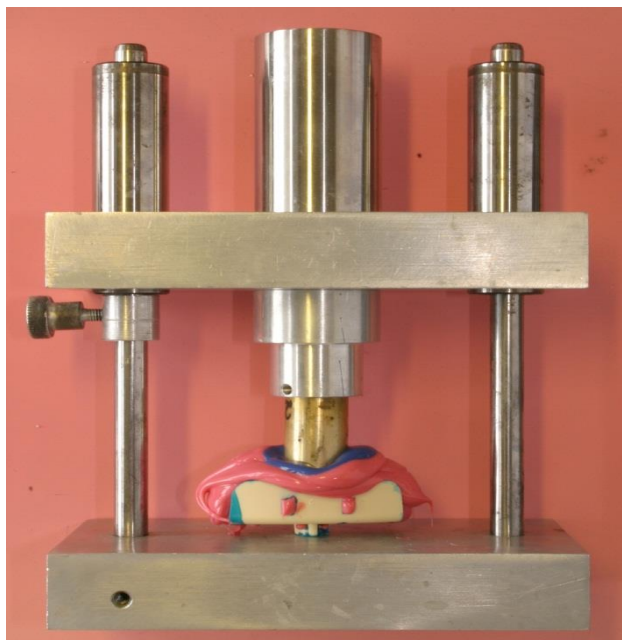


Fig. 10: Impression making for the prepared specimen.

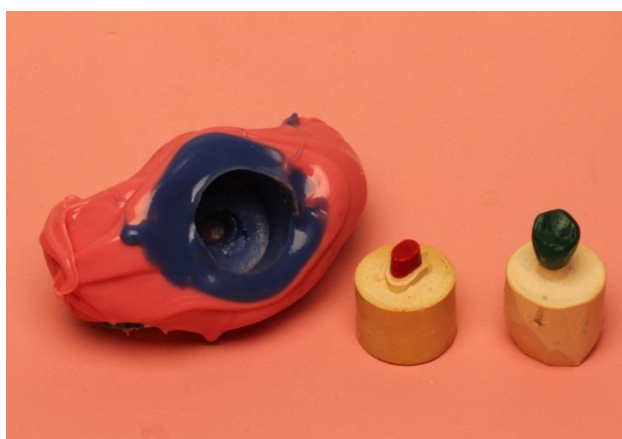


Fig. 11: Final impression and die stone.

To obtain identical crown dimensions in all specimens, a stylized reference crown (Fig. 12) with a 30-degree angulation of the buccal cusp to the

vertical tooth axis was created in wax (Crowax; Renfert GmbH, Hilzingen, Germany).

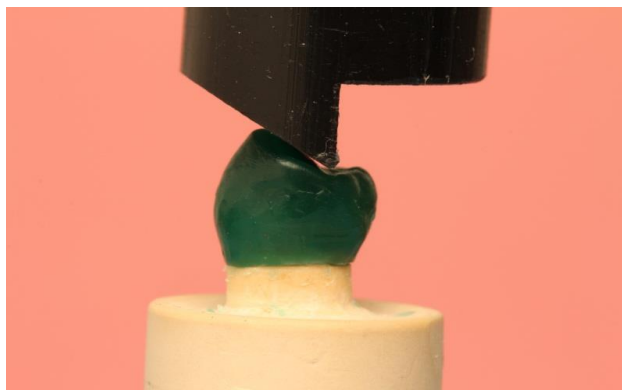


Fig. 12: Controlling of the inclination of the buccal cusp slope with parallelometer.

Then, the crowns were duplicated onto the other dies by inserting heated liquid wax into a silicone mold (Deguform, Degudent, Hanau-Wolfgang, Germany). The crown wax patterns were measured using a wax gauge to assure that all the patterns have the same dimensions. The crown wax patterns were invested and cast (Fig. 13) in cobalt-chromium alloy (Wirobond C; Bego, Bremen, Germany) following the instructions of the manufacturer. The internal surfaces of the crowns were airborne-particle abraded with 50 μ m alumina (Aluminum Oxide Abrasive; Heraeus Kulzer GmbH, Germany) at 0.25 MPa pressure and then ultrasonically cleaned in 96% isopropanol (German Federal Monopoly Administration for Spirits).



Fig. 13: Cast crowns.

The tooth preparations were cleaned with a rotary brush (Omnident; Rodgau, Germany) and pumice (Sterilbimspaste; Ernst Hinrichs GmbH, Goslar, Germany). Then, the crowns were cemented using glass-ionomer cement (Ketac Cem Maxicap; 3M/ESpe, Seefeld, Germany) which was mixed according to the manufacturer's instructions. During the cementing procedures, each crown was held in place for 7 minutes under a 5-kg load using custom made device (Figs. 14 & 15).



Fig. 14: Crown cementation.



Fig. 15: Specimens after cementation.

After storing the specimens in deionized water at 37 °C, all specimens underwent combined masticatory loading simulation in a dual-axis masticatory

simulator [103] (Willytec, Munich, Germany) with a nominal load of 5 Kg for 1.2 million cycles and thermocycling at 5°C- 55°C for 6499 cycles (Fig. 16).

The masticatory simulator has eight identical sample chambers and two stepper motors which allow computer-controlled vertical and horizontal movements between two antagonistic specimens in each specimen chamber. The masticatory cycle in this study consisted of three phases: contact with a vertical load of (5 Kg), horizontal sliding of 0.3 mm, and separating the teeth and their antagonistic material. The masticatory load curve is programmed by the combination of horizontal and vertical movements.



Fig. 16: Multifunction chewing simulator (Willytec)

The computer unit controls the mechanical motion and the water flow of cold and warm water baths for the thermal cycling of the specimens. The test parameters of the chewing simulator are listed in Table 2.

After masticatory simulation, all specimens were carefully examined under low power (25 X) stereo-magnification (Leica M420; Leica Microsystems GmbH, Wetzlar, Germany) to detect incipient fracture.

Table 2. Test parameters	
Cold/hot bath temperature	5°C/55°C
Vertical movement	6 mm
Rising speed	55 mm/s
Descending speed	30 mm/s
Weight per specimen	5 kg
Kinetic energy	2,250 x 10 ⁻⁶ J
Dwell time	30 s
Horizontal movement	0.3 mm
Forward speed	30 mm/s
Backward speed	55 mm/s
Cycle frequency	1.3 Hz

2.3. Fatigue loading device

All specimens which survived the dynamic loading were quasi-statically loaded with a crosshead speed of 1 mm/min at an angle of 30 degrees to the longitudinal axis of the tooth in a universal testing machine (Zwick Z010/TN2A; Zwick, Ulm, Germany) until they were fractured (Fig. 17). Loading was on the lingual incline of the buccal cusp at a distance of 2 mm from the central fossa of the crown (Fig. 18). Specimens were visually examined for the type and location of failure, as well as the direction of failure.



Fig. 17: Universal testing machine Z010/TN2A

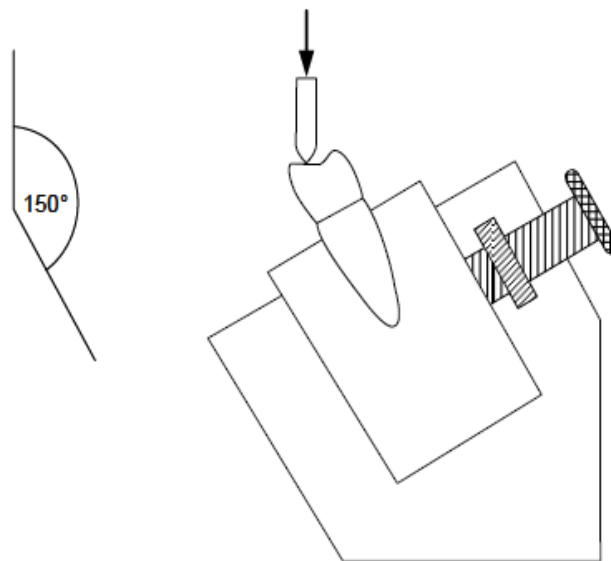


Fig. 18: Schematic representation of the fracture load tests in the universal testing machine

2.4. Statistical analysis

Data were explored for normality using Kolmogorov-Smirnov and Shapiro-Wilk tests, which showed that data were normally distributed. Levene test for homogeneity of variance indicated homogeneity of variances between groups. Two-way analysis of variance (ANOVA) was used to compare fracture resistance means among the five groups followed by multiple comparisons using Tukey HSD test ($\alpha=.05$). The confidence level was 95%. Statistical analysis was performed with SPSS 18.0 (SPSS 18.0 for Windows; SPSS, Inc, Chicago, IL, USA).

According to the significance level ($\alpha=.05$) and the sample size ($n = 8$), the test of choice had adequate power to detect statistical differences which could be used to provide clinical recommendations ($F = 0.11$). Failure modes were recorded and statistically analyzed with Chi-square (X^2) testing for significant correlation between design and failure modes.

3. RESULTS

None of the specimens failed during masticatory simulation. The mean values of the fracture strength and standard deviations are displayed in Table 3. They ranged from 679.5 ± 164.9 N to $1,084.50 \pm 269.9$ N. The fracture resistance of each group increased when the ferrule height increased and a second residual coronal wall existed. Two-way ANOVA (Table 4) indicated that both the ferrule height and the number of residual walls had a significant influence on the fracture resistance ($P \leq .001$ and $P = .006$, respectively). There was no statistically significant interaction between the factors ferrule height and residual coronal walls ($P = 0.889$). Tukey's post hoc test at a significance level of 0.05 determined the differences between subgroups (Table 5, 6).

Table 3. Fracture loads in N (means \pm standard deviations)

Group	1 residual coronal wall	2 residual coronal walls
A	A1: 679.5 ± 164.9	A2: 754.9 ± 193.4
B	B1: 742.6 ± 166.6	B2: 824.0 ± 157.7
C	C1: 824.7 ± 194.3	C2: 933.9 ± 145.5
D	D1: 854.0 ± 232.1	D2: 1052.3 ± 187.0
E	E1: 932.2 ± 206.4	E2: $1,084.5 \pm 269.9$

- A: no ferrule; B: 0.5 mm ferrule; C: 1 mm ferrule; D: 1.5 mm ferrule; E: 2 mm ferrule height

- 1: 1 residual coronal wall; 2: 2 residual coronal walls.

Results of the static fracture load testing for all treatment groups are shown in a box plot representation in Fig. 19.

Table 4. Summary of 2-way ANOVA of main factors

Source of variation	Sum of Squares	df ^x	Mean Square	F	p
Ferrule	912096.5	4	228024.1	6	<.001
Wall	304057.8	1	304057.8	8	.006
Ferrule X Wall	42919.2	4	10729.8	.3	.889
Error	2663122.5	70	38044.6		
Total	6.4	80			

^xDegrees of freedom.

Table 5. Multiple comparisons in subgroups with 1 wall (Tukey HSD)

(I) Ferrule height	(J) Ferrule height	Mean Difference (I-J) in N	Std. Error	Sig.
0 mm ferrule	0.5 m ferrule	-63.13	97.255	.966
	1 m ferrule	-145.25	97.255	.573
	1.5 mm ferrule	-174.50	97.255	.393
	2 mm ferrule	-252.75	97.255	.092
0.5 mm ferrule	0 m ferrule	63.13	97.255	.966
	1 m ferrule	-82.13	97.255	.915
	1.5 mm ferrule	-111.38	97.255	.782
	2 mm ferrule	-189.63	97.255	.311
1 mm ferrule	0 m ferrule	145.25	97.255	.573
	0.5 m ferrule	82.13	97.255	.915
	1.5 mm ferrule	-29.25	97.255	.998
	2 mm ferrule	-107.50	97.255	.803
1.5 mm ferrule	0 m ferrule	174.50	97.255	.393
	0.5 m ferrule	111.38	97.255	.782
	1 m ferrule	29.25	97.255	.998
	2 mm ferrule	-78.25	97.255	.927
2 mm ferrule	0 m ferrule	252.75	97.255	.092
	0.5 m ferrule	189.63	97.255	.311
	1 m ferrule	107.50	97.255	.803
	1.5 mm ferrule	78.25	97.255	.927

Table 6. Multiple Comparisons in subgroups with 2 walls (Tukey HSD)

(I) Ferrule height	(J) Ferrule height	Mean Difference (I-J) in N	Std. Error	Sig.
0 mm ferrule	0.5 m ferrule	-69.13	97.794	.954
	1 m ferrule	-179.00	97.794	.373
	1.5 mm ferrule	-297.50	97.794	.034
	2 mm ferrule	-329.63	97.794	.015
0.5 mm ferrule	0 m ferrule	69.13	97.794	.954
	1 m ferrule	-109.88	97.794	.793
	1.5 mm ferrule	-228.38	97.794	.158
	2 mm ferrule	-260.50	97.794	.080
1 mm ferrule	0 m ferrule	179.00	97.794	.373
	0.5 m ferrule	109.88	97.794	.793
	1.5 mm ferrule	-118.50	97.794	.745
	2 mm ferrule	-150.62	97.794	.544
1.5 mm ferrule	0 m ferrule	297.50	97.794	.034
	0.5 m ferrule	228.38	97.794	.158
	1 m ferrule	118.50	97.794	.745
	2 mm ferrule	-32.12	97.794	.997
2 mm ferrule	0 m ferrule	329.63	97.794	.015
	0.5 m ferrule	260.50	97.794	.080
	1 m ferrule	150.62	97.794	.544
	1.5 mm ferrule	32.12	97.794	.997

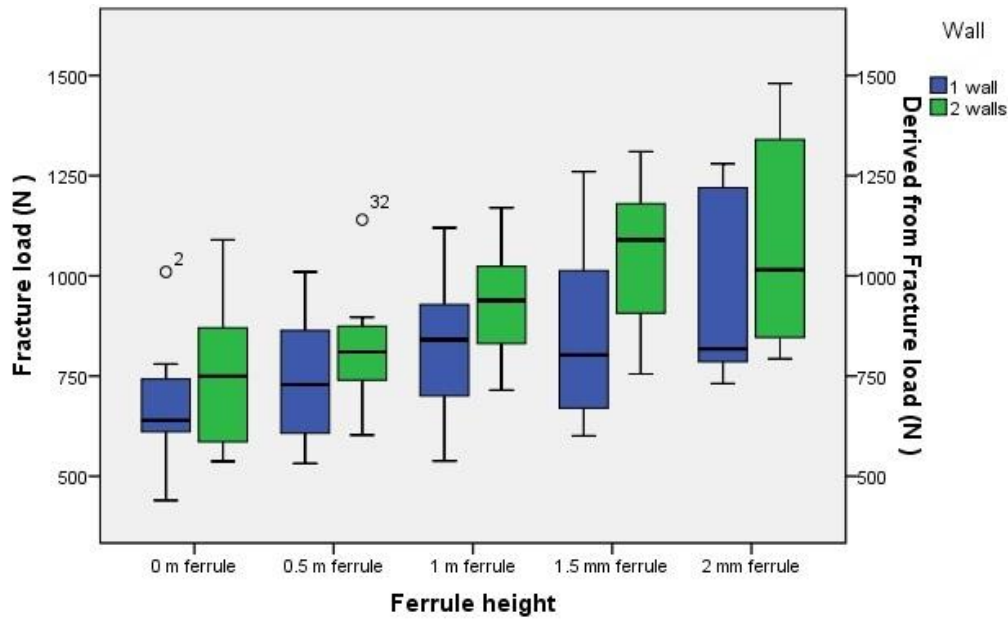


Fig. 19: A box plot representation of the fracture load testing.

Chi-square (X^2) test revealed that there were no significant differences in fracture modes among the 10 groups (Table 7). The mode of failure was determined by visual inspection of all specimens. There were two typical root fracture modes: cervical third fracture (favorable mode), middle and apical third (catastrophic mode). All groups had almost complete favorable fracture mode (Figs. 20a & b). The type of fracture behavior and the frequency are illustrated in Fig. 21. The fracture behavior in A1, B1, and C1 subgroups with 1 residual coronal wall differed slightly from that in subgroups with 2 residual coronal walls, where the fracture line crossed into the dental substance which began further facially. Nearly all the teeth had a facial fracture by 2–4 mm below the crown margin and lingual along the crown margin.

RESULTS

Table 7. Fracture mode of each group

Failure mode	Groups									
	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2
favorable	8	8	7	8	7	7	7	7	8	8
	(100%)	(100%)	(87.5%)	(100%)	(87.5%)	(87.5%)	(87.5%)	(87.5%)	(100%)	(100%)
Non-favorable	0	0	1	0	1	1	1	1	0	0
	(0%)	(0%)	(12.5%)	(0%)	(12.5%)	(12.5%)	(12.5%)	(12.5%)	(0%)	(0%)

Group: $X^2 = 4.324$; DF = 9; $P = 0.661$.

Fracture mode: $X^2 = 6.452$; DF = 9; $P = 0.632$.



Fig. 20 a: Fracture mode of a specimen with one dentinal wall (buccal wall).



Fig. 20b: Fracture mode of a specimen with two dentinal walls (buccal & lingual wall).

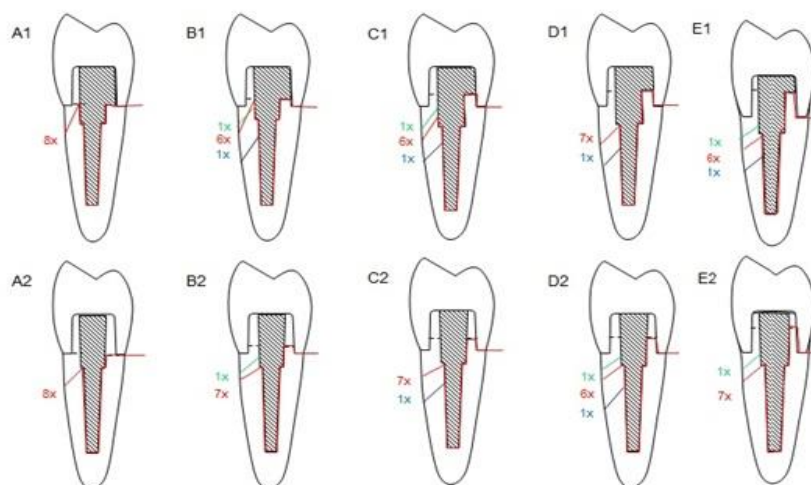


Fig. 21: Schematic representation of the fracture modes and their frequency.

4. DISCUSSION

The present study investigated the influence of five ferrule heights on the fracture resistance of crowned lower premolars. Teeth in subgroups were either with 1 or 2 residual coronal dentin walls. Eight specimens per group were exposed to thermal cycling and mechanical loading and loaded until fracture. Eight specimens per subgroup were chosen because 8 specimens can be loaded at a time in the masticatory simulator. A thymol solution is an antifungal agent [5]. For this reason 0.1 % thymol was used since the teeth had to be stored for an extended period as collection proceeded. Teeth were generally prepared; however, with their finish lines following the coronal extension of the gingival tissue level interproximally. To mimic this clinical condition, the finish lines in this study were mesial and distal 1 mm more coronal than the facial and lingual surfaces and which were cervical to the CEJ. Different materials have been used to simulate the periodontal ligament [35, 69, 96]. However, the benefits of using such materials are questionable since the elasticity is different from that of the periodontal membrane and the elastic nature of the alveolar bone is not taken into account. Moreover, using an artificial periodontal ligament might be important when testing splinted restorations on multiple teeth to achieve differential abutment tooth mobility but the benefit of using an artificial periodontal ligament when testing single tooth is not so clear. An artificial membrane would have absorbed some stress during dynamic loading; however as in our study the restored teeth did not fail during dynamic loading our somewhat "harder" test conditions did not affect the survival of teeth. Teeth in this study were directly mounted into auto-polymerizing resin and the force was absorbed by the tooth tissue primarily, which may have resulted in a lower failure load than would be seen *in vivo*.

A custom-made parallelometer was used to standardize the preparation for all specimens and the required dimensions were obtained prior to core

fabrication by reducing the tooth structure in a stepwise manner using a digital sliding caliper to control dimensions. After core fabrication only a low speed handpiece with a fine grain diamond was used to finish the preparation and only a minimal additional amount of dentin was removed by that procedure. It must be admitted that this resulted in a slight overestimation of the remaining coronal tooth structure. However, as this was done in the same manner in each group it is assumed that this did not affect the results considerably.

A post length of 10.5 mm was prepared to ensure an adequate post length [5, 41, 46]. Conventional cements are non-adhesive and rely primarily on mechanical interlocking to retain the dowel core. These inorganic cements have a relative high rigidity and low elasticity. The advantages of using a resin cementation system as in this study are supported by results of the studies conducted by Mendoza and Eakle [67] and Mendoza *et al.* [68].

Composite resin core material was used in this study since it has a higher fracture resistance than the other core materials such as amalgam and glass ionomer cement [25, 64, 108] because a stronger union between core and tooth structure was established using the adhesive bonding agents. Humans perform an average of 250,000 chewing cycles per year [32, 90]. In this study, 1,200,000 load cycles were performed [32], estimated to equate to 5 years of normal function. Force applied at 150° from the long axis of the mandibular premolar was employed to simulate functional working-side buccal cusp loading.

The first hypothesis that the ferrule height would not affect the fracture resistance of crowned premolars was rejected. The ferrule height had a significant influence on the final fracture resistance ($P \leq .001$), which was reduced to approximately 37% when teeth with 2 mm ferrule height were compared with teeth without ferrule. In addition, the amount of residual coronal dentin had a significant influence on the final fracture resistance of the restored

teeth ($P=.006$). Therefore, the second hypothesis that the amount of residual coronal dentin would not affect the fracture resistance of crowned premolars was also rejected.

Unfortunately, the authors identified no other studies that evaluated the effect of the ferrule height and the number of residual walls on the fracture strength of the crowned premolars. None of the specimens failed during masticatory simulation. Therefore, the fracture resistance of the aged specimens to quasi-static loading could be determined in all groups.

The fracture resistance of the restored premolars ranged from 679.5 ± 164.9 (group A1) to 1084.5 ± 269.9 N (group E2), which can be compared well to previous in-vitro studies [2, 63, 78]. The results of the fracture resistance test in subgroups of teeth having 1 remaining coronal dentine wall showed that increasing ferrule height improved the fracture resistance of ETT restored with prefabricated posts. This suggests that more ferrule height required a higher value of compressive load to promote root fracture. The lowest fracture resistance values were found for the subgroups without a ferrule. These results may be explained due to the fact that greater remaining tooth structure results in a stronger tooth [2, 13, 75, 78]. The greater amount of dentin can redistribute and dissipate of a larger force. The results of the fracture resistance test in subgroups of teeth having 2 remaining coronal dentine walls showed that the amount 0.0 mm, 0.5 mm or 1 mm of ferrule height did not significantly influence the fracture resistance of crowned premolars (Table 6). These findings are in agreement with those of previous studies which recommended a minimal height of 1.5 to 2 mm of intact tooth structure above the crown margin for 360 degrees around the circumference of the tooth preparation as a rational guideline for the ferrule effect [9, 60, 72, 112, 117]. This could be explained by that even if the availability of 2 residual coronal walls, the role of the absence or

extremely small ferrule height may be masked by the presence of the cohesive unit (tooth, post, core, and crown) as previously explained.

The results of the fracture resistance test in subgroups of teeth having 2 remaining coronal dentine walls showed that the amount 1.5 mm and 2 mm of ferrule height significantly increased the fracture resistance of crowned premolars ($P=.034$ and $P=.015$, respectively) as compared to a smaller ferrule height (Table 6). These results are in agreement with those of previous studies [2, 60, 117]. This could be explained by the increasing of the ferrule height, which plays an important role in resistance to fracture load. Several studies stated that the amount of residual coronal dentin following endodontic treatment appears to be a crucial factor for the prognosis of the tooth [23, 38, 80]. Mangold and Kern [63] reported that the fracture resistance of endodontically treated premolars was dependent on the number of residual coronal dentin walls (at least 2 walls to avoid the use of other means, like GFPs, to raise the resistance against fracture load). The role of the ferrule is: reinforcing the teeth at its external surface and redistributing the applied forces, which concentrate at the narrowest point around the circumference of the tooth [5, 100] and helps to maintain the integrity of the cement seal of the crown [60].

All groups had almost complete favorable fracture mode. These findings are in agreement with those of previous studies which stated that prefabricated fiber-reinforced composite posts frequently showed more favorable failure modes compared with metal posts [27, 39, 96]. This can be explained by the low rigidity of GFPs. It has been suggested that GFPs show reduced stress transmission to the root because of similar elasticity compared to dentin (E-modulus of GFPs = 9-50 GPa; dentin = 14-18 GPa) [39, 59, 62]. However, in light of recently published clinical studies showing higher failure rates with glass-fiber posts [74, 93] than with zirconia ceramic posts [20] the validity of this concept might be questioned.

In light of the results of this study, preservation of tooth structure is an important procedure and the maximizing the residual amount of coronal tooth structure can increase the tooth resistance against fracture load. As in many in-vitro studies, it is difficult to extrapolate the results of this study directly to a clinical situation.

The limitations of this study include; the natural variation among the natural teeth, lack of a periodontal ligament, and the fracture resistance was determined by applying a heavy load to a single point; by contrast, in vivo failure typically occurs in response to light or moderate loads applied repeatedly over a long period. Therefore, further research is needed to evaluate the effects of the non-uniform ferrule height and the type of a post on the fracture resistance of ETT.

5. CONCLUSIONS

Within the limitations of this in-vitro study, the following conclusions can be drawn:

1. Increasing the ferrule height will increase the fracture resistance of ETT restored with prefabricated posts and cores significantly.
2. The preservation of two dentinal walls will increase the resistance of ETT restored with a prefabricated post and core significantly when compared with teeth with one dentinal wall.

Therefore, residual walls should be preserved and the ferrule height should be kept maximal to increase the fracture resistance of ETT.

6. SUMMARY

There were no studies that evaluated the effect of the ferrule height and the number of residual walls on the fracture resistance of the endodontically treated teeth simultaneously (ETT). Therefore, the aim of this study was to evaluate the effect of different ferrule heights and varying degrees of substance loss on the fracture resistance of endodontically treated premolars.

Eighty extracted and endodontically treated lower premolars were used and divided into 5 test groups (n=16) depending on the ferrule height: group A: specimens without circumferential ferrule; group B: circumferential ferrule 0.5 mm above the finish line; group C: circumferential ferrule 1 mm above the finish line; group D: circumferential ferrule 1.5 mm above the finish line; group E: circumferential ferrule 2 mm above the finish line. Teeth in subgroups were either with 1 or 2 residual coronal dentin walls which were 3 mm in height and 1 mm in thickness. All specimens were then restored with cast crowns and subjected to dynamic loading in a masticatory simulator for 1,200,000 loading cycles with a nominal load of 5 Kg at 1.2 Hz combined with thermal cycling (5-55°C, dwell time 30s). Then specimens were quasi-statically loaded at 30 degree in a universal testing machine until fracture. Data were analyzed with 2-way ANOVA ($\alpha=.05$), followed by multiple comparisons using Tukey HSD test ($\alpha=.05$).

Mean (SD) failure loads for all groups ranged from 679.5 ± 164.9 N to 1084.5 ± 269.9 N. Two-way ANOVA revealed that both the ferrule height and the number of residual coronal walls had a significant influence on the fracture resistance ($P<0.001$ and $P=0.006$, respectively). Significant increases were produced in the final fracture resistance, when the ferrule height were increased, which were reduced to approximately 37% when teeth with 2 mm ferrule height were compared with teeth without a ferrule. Under the conditions of this in-vitro study, increasing the number of residual coronal walls and ferrule height had a

significant effect on the fracture resistance of endodontically treated premolars restored with prefabricated posts.

7. ZUSAMMENFASSUNG

Das Ziel der vorliegenden In-vitro-Studie war es, den Einfluss von der Höhe der Wurzelumfassung und des Substanzverlust auf die Bruchfestigkeit endodontisch behandelter Prämolaren, die mit Glasfaserstiften versorgt wurden, zu evaluieren.

Achtzig extrahierte und endodontisch behandelte untere Prämolaren wurden in 5 Versuchsgruppen ($n = 16$) in Abhängigkeit von der Höhe ihrer Wurzelumfassung unterteilt: Gruppe A (ohne Wurzelumfassung), Gruppe B (0,5 mm Höhe der Wurzelumfassung), Gruppe C (1 mm Höhe), Gruppe D (1,5 mm Höhe) und Gruppe E (2 mm Höhe). Die Zähne in den Untergruppen wiesen entweder eine oder zwei verbliebene Dentinwände auf ($n = 8$). Alle Zähne wurden adhäsiv mit Kompositkunststoff und einem adhäsiv befestigten Glasfaserstift restauriert. Die Präparation erfolgte mit einer 0,8 mm breiten abgerundeten Stufe. Anschließend wurden alle Zähne mit Vollgusskronen versorgt, die mit Glasionomer-Zement konventionell befestigt wurden. Danach wurden alle Proben in einem Kausimulator für 1.200.000 Belastungszyklen mit einer Nennlast von 5 kg bei 1,2 Hz mit thermischen Zyklen (5-55 ° C, Verweilzeit 30 s) kombiniert unterzogen und dynamisch belastet. Die Proben wurden quasi-statisch unter einem Winkel von 30 Grad in einer Universal-Prüfmaschine bis zum Bruch belastet. Die Daten wurden mit zweifaktorieller Varianzanalyse und multiplen Gruppenvergleichen ($\alpha = 0,05$), analysiert.

Es wurden signifikante Unterschiede zwischen den Mittelwerten der Bruchfestigkeiten der Test-Gruppen gefunden. Die mittlere Bruchfestigkeit variierte zwischen $679,5 \pm 164,9$ N und $1084,5 \pm 269,9$ N. Die Varianzanalyse zeigte, dass sowohl die Höhe der Wurzelumfassung ($P \leq 0,001$) als auch die Anzahl der verbleibenden Wände ($P = 0,006$) einen signifikanten Einfluss auf die Bruchfestigkeit hatten. Die Erhöhung der Wurzelumfassung führte zu einer

signifikanten Erhöhung der Bruchfestigkeit, die etwa 37% reduziert wurde, wenn die Zähne mit 2 mm Höhe der Wurzelumfassung mit Zähnen ohne Wurzelumfassung verglichen wurden. Es gab keine statistisch signifikante Wechselwirkung zwischen der Höhe der Wurzelumfassung und der Anzahl der verbliebenen Wände ($P=0,956$).

Die vorliegende Studie weist nach, dass sowohl die Höhe der Wurzelumfassung als auch der Anzahl der verbliebenden Wände einen signifikanten Einfluss auf die Bruchfestigkeit von mit endodontisch behandelten und mit Wurzelstiften versorgten Prämolaren haben.

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10. DEDICATION

Finally, I dedicate this thesis to:

My Prophet MohammedPeace be upon him

My parents Ahmed and Wala'a

My wife Nedhal

My brothersMohammed and Ali

My sistersGaitha, Ahlam, Elham and Fatima

My children Omar, Hagar and Ahmed

Thank you my family for your constant support, love, and encouragement for me to complete this Doctorate's program and make this thesis possible.

11. C.V

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- Yemen Dental Association
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- One-year in oral surgery in Faculty of dentistry (Damascus -Syria).
- Course in Implantology (Anthogyr System).
- Course in data analysis and using S P S S program in Christian-Albrechts University in Kiel.

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- Arabic (Mother language): excellent reading, writing, speaking.
- English: Very good reading, writing, speaking.
- Deutsch (Germany): Good reading, writing, speaking.

HOBBIES: Reading, walking, and playing football.

12. APPENDIXES

Table 8 : Fracture strength of Subgroup A1	
Description	Fracture resistance (N)
Without ferrule + 1 wall	780
	1010
	615
	624
	655
	705
	440
	607
Mean	679.5
Standard deviation	164.9

Table 9: Fracture strength of Subgroup A2	
Description	Fracture resistance (N)
Without ferrule + 2 walls	860
	634
	881
	538
	831
	1090
	668
	537
Mean	754.9
Standard deviation	193.3

Table 10: Fracture strength of Subgroup B1	
Description	Fracture resistance (N)
0.5 mm ferrule height + 1 wall	685
	925
	772
	532
	1010
	802
	630
585	
Mean	742.5
Standard deviation	166.7

Table 11: Fracture strength of Subgroup B2	
Description	Fracture resistance (N)
0.5 mm ferrule height + 2 walls	696
	784
	603
	897
	831
	789
	852
1140	
Mean	824
Standard deviation	157.7

Table 12: Fracture strength of Subgroup C1	
Description	Fracture resistance (N)
1 mm ferrule height + 1 wall	847
	1120
	847
	820
	538
	581
	1010
	835
Mean	824.8
Standard deviation	194.3

Table 13: Fracture strength of Subgroup C2	
Description	Fracture resistance (N)
1 mm ferrule height + 2 walls	841
	977
	1070
	1170
	715
	901
	976
	821
Mean	933.9
Standard deviation	145.6

Table 14: Fracture strength of Subgroup D1	
Description	Fracture resistance (N)
1.5 mm ferrule height + 1 wall	601
	1260
	645
	701
	695
	904
	976
1050	
Mean	854
Standard deviation	232.1

Table 15: Fracture strength of Subgroup D2	
Description	Fracture resistance (N)
1.5 mm ferrule height + 2 walls	755
	1200
	1160
	1310
	977
	837
	1120
1060	
Mean	1052.4
Standard deviation	187

Table 16: Fracture strength of Subgroup E1	
Description	Fracture resistance (N)
2 mm ferrule height + 1 wall	838
	1080
	1210
	731
	781
	790
	798
1230	
Mean	932.3
Standard deviation	206.4

Table 17: Fracture strength of Subgroup E2	
Description	Fracture resistance (N)
2 mm ferrule height + 2 walls	793
	950
	1390
	875
	1290
	1080
	1480
818	
Mean	1084.5
Standard deviation	269.9