Aus der Klinik für Zahnärztliche Prothetik, Propädeutik und Werkstoffkunde

(Direktor: Prof. Dr. M. Kern)

im Universitätsklinikum Schleswig-Holstein, Campus Kiel

an der Christian-Albrechts-Universität zu Kiel

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]

Inauguraldissertation

zur Erlangung der Würde eines Doktors der Zahnheilkunde

der Medizinischen Fakultät der Christian-Albrechts-Universität zu Kiel

vorgelegt von

ABDULAZIZ SAMRAN

aus Al-baidha, Jemen

Kiel 2014

1. Berichterstatter: Prof. Dr. Matthias Kern

2. Berichterstatter: Priv.-Doz. Dr. Katrin Hertrampf

Tag der mündlichen Prüfung: 12.12.2014

Zum Druck genehmigt, Kiel, den 15.12.2014

gez.:

CONTENTS

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].

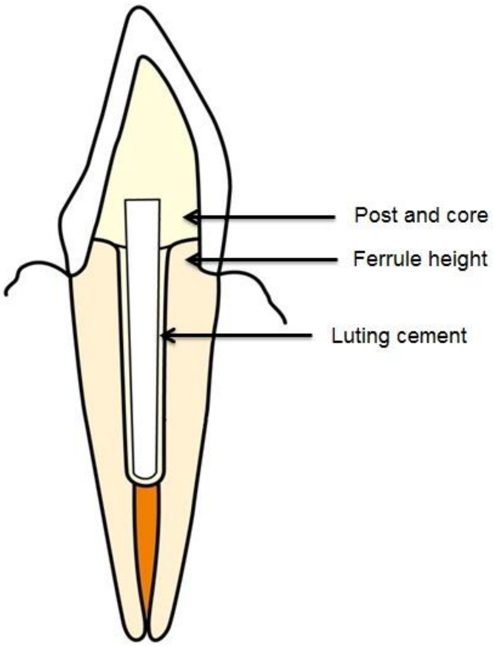

Fig. 1 The ferrule effect.

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].

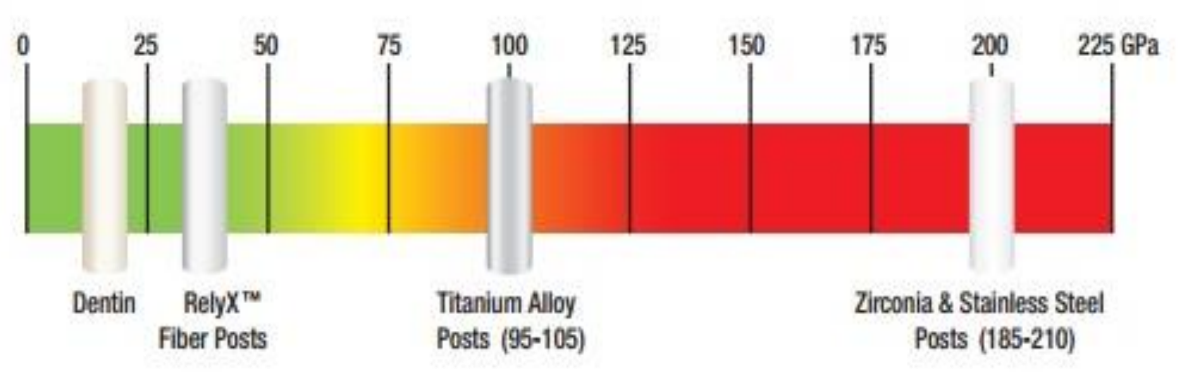

Fig. 2: Elasticity modulus (GPa) of dentin and post materials (3M ESPE internal data).

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.

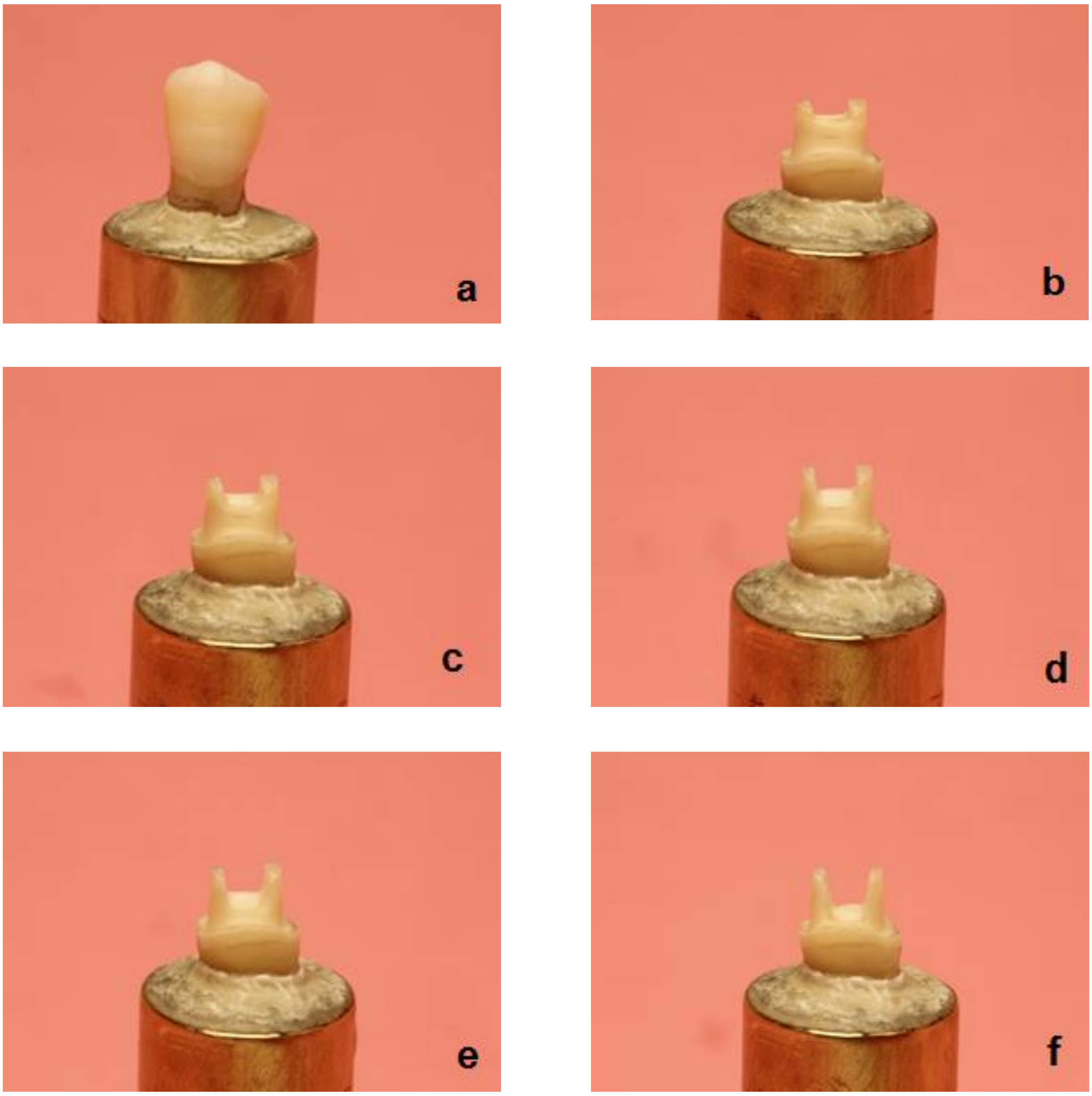

Fig. 4: Prepared specimens with two dentinal wall and different ferrule height: a) sound specimen (without any preparation), b) with 2 mm ferrule height, c) with 1.5 mm ferrule height, d) with 1 mm ferrule height, e) with 0.5 mm ferrule height, f) without ferrule.

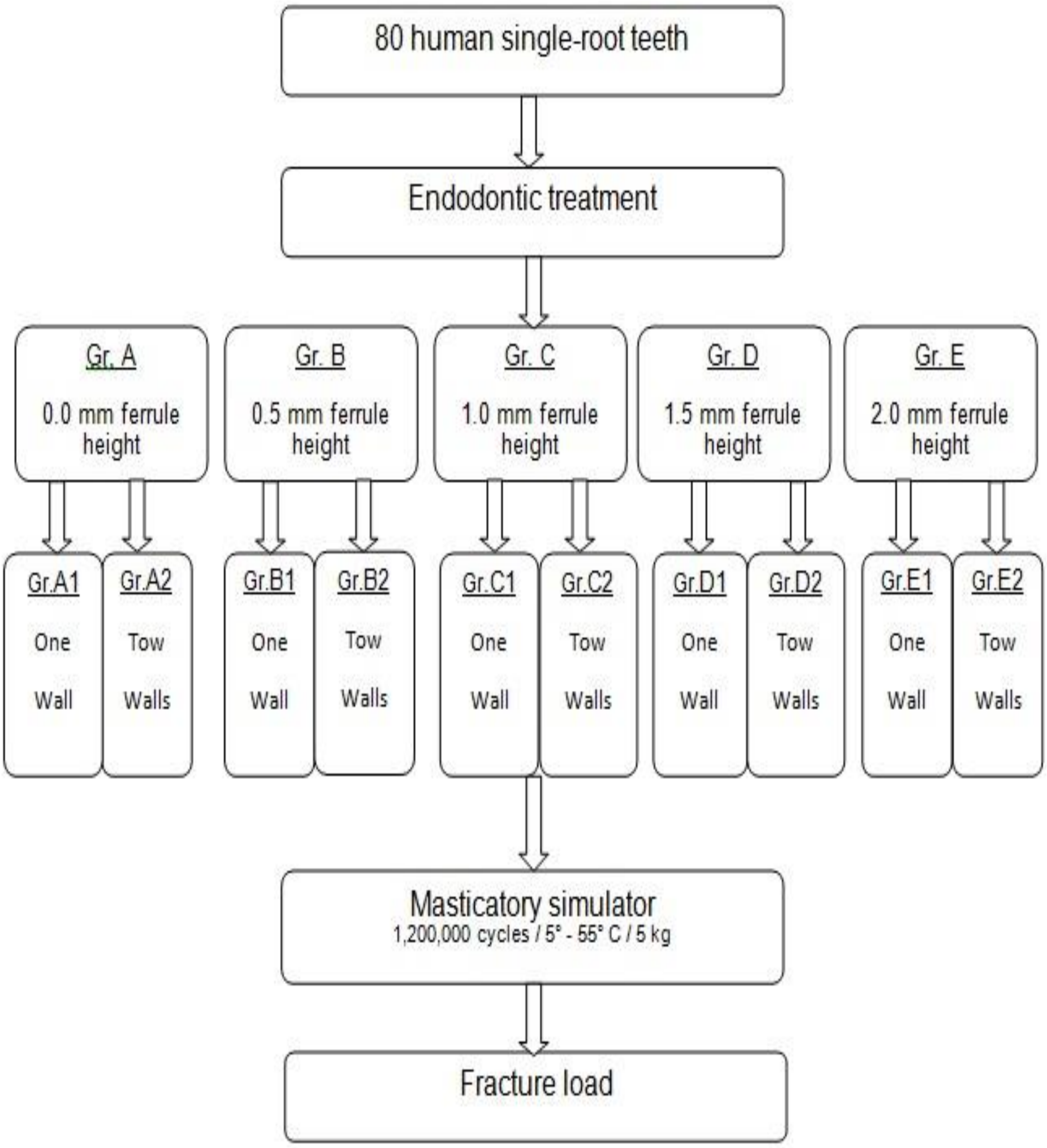

Fig. 5: Flow chart of study design.

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).

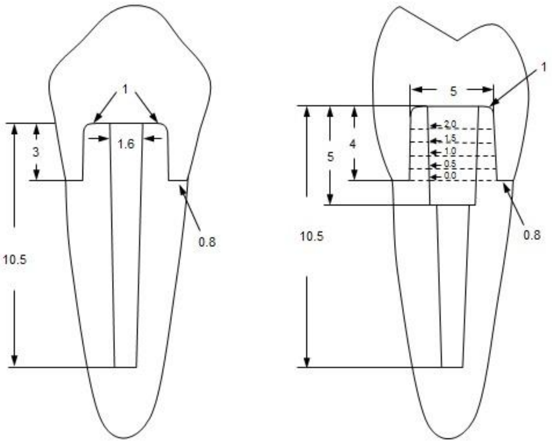

Fig. 9: Dimensions of preparation, restoration and ferrule height (in mm).

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).

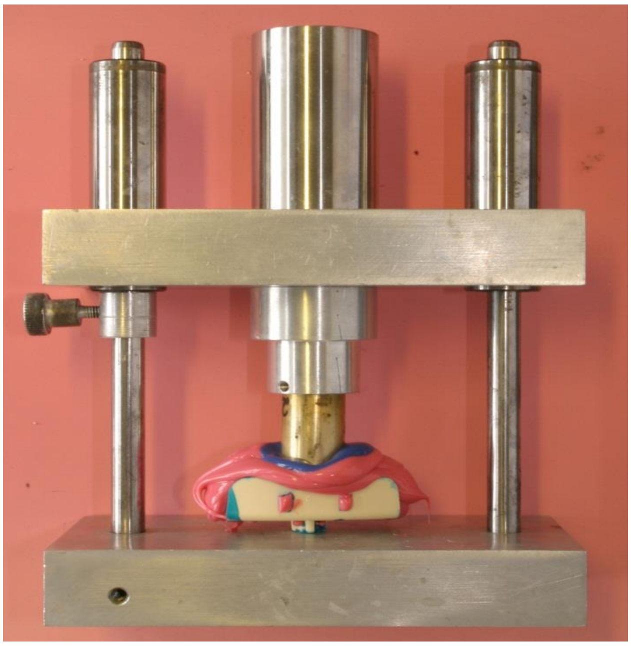

Fig. 10: Impression making for the prepared specimen.

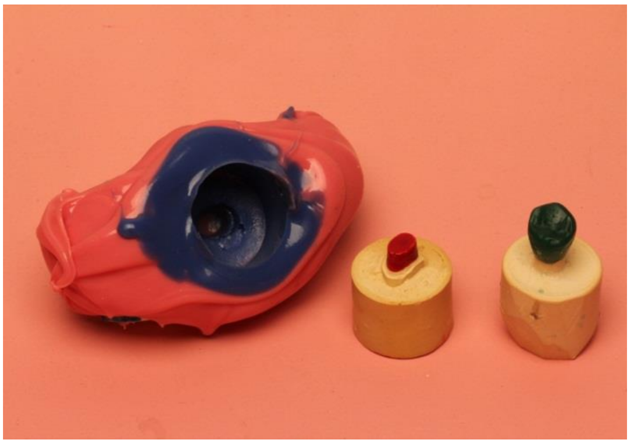

Fig. 11: Final impression and die stone.

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).

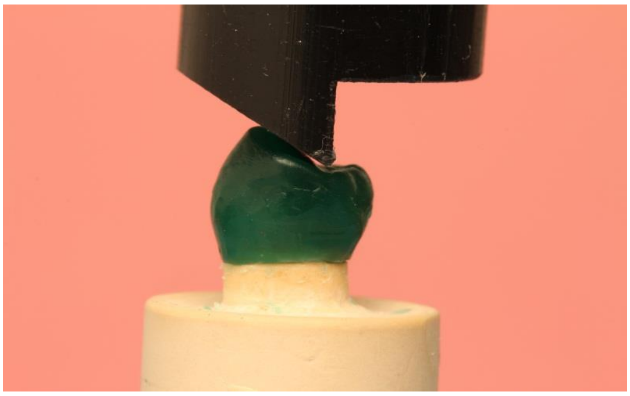

Fig. 12: Controlling of the inclination of the buccal cusp slope with parallelometer.

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 µm 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).

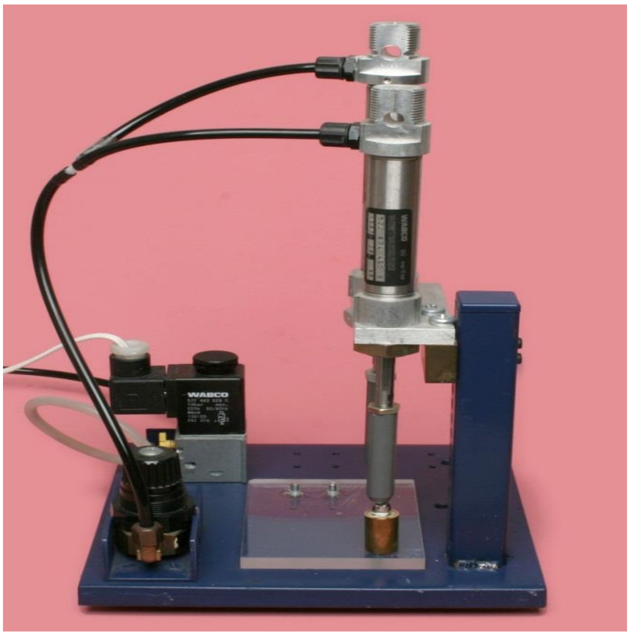

Fig. 14: Crown cementation.

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

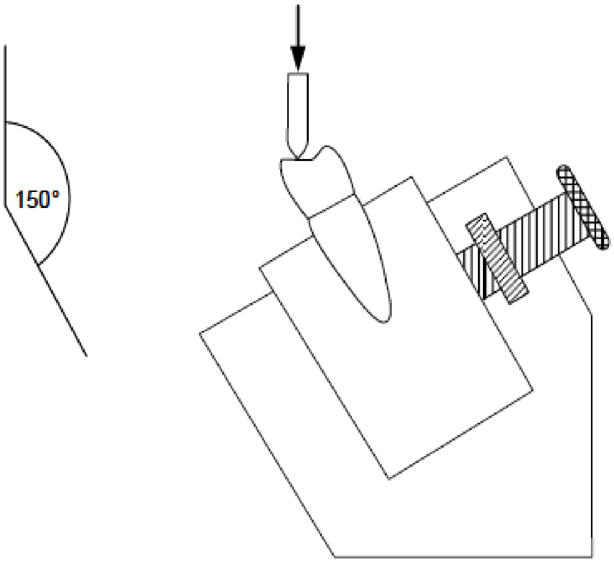

Fig. 18: Schematic representation of the fracture load tests in the universal testing machine

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 (α=.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 (α=.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 ±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 ± 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 ± 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			

^{x} Degrees 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

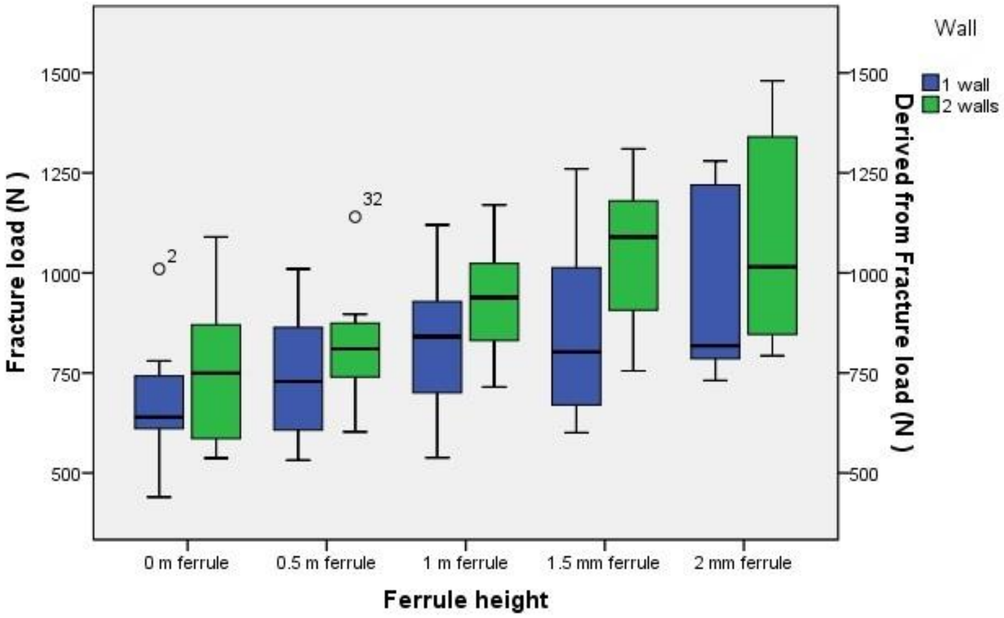

Fig. 19: A box plot representation of the fracture load testing.

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.

Table 7. Fracture mode of each group

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

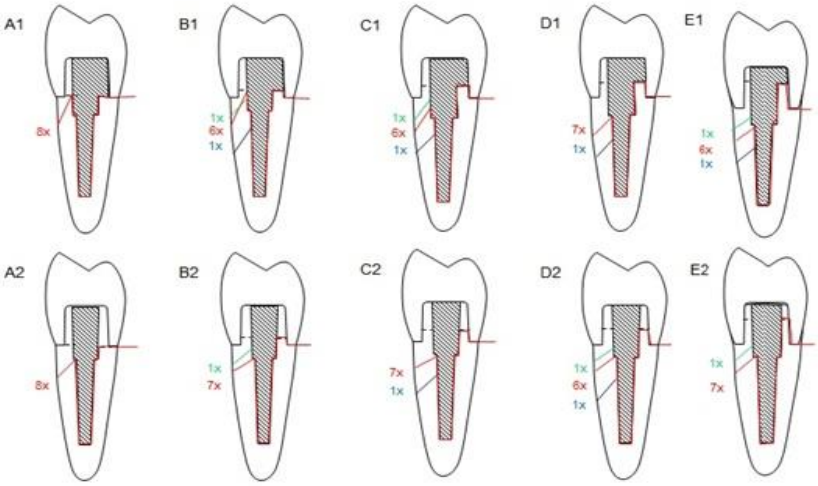

Fig. 21: Schematic representation of the fracture modes and their frequency.

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± 269.9N (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 1or 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 ± 164,9 N und 1084,5 ± 269,9 N. Die Varianzanalyse zeigte, dass sowohl die Höhe der Wurzelumfasung ($P \leq 0{,}001$) 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.

8. REFERENCES

[1] Abadie FR. Cast 'headed' post-cores to resist fracture of endodontically treated anterior teeth. J Prosthet Dent 1988; 60: 660-1.

[2] Akkayan B. An in vitro study evaluating the effect of ferrule length on fracture resistance of endodontically treated teeth restored with fiber-reinforced and zirconia dowel systems. J Prosthet Dent 2004; 92: 155-62.

[3] Akkayan B, Gulmez T. Resistance to fracture of endodontically treated teeth restored with different post systems. J Prosthet Dent 2002; 87: 431-7.

[4] Al-harbi F, Nathanson D. In vitro assessment of retention of four esthetic dowels to resin core foundation and teeth. J Prosthet Dent 2003; 90: 547-55.

[5] al-Hazaimeh N, Gutteridge DL. An in vitro study into the effect of the ferrule preparation on the fracture resistance of crowned teeth incorporating prefabricated post and composite core restorations. Int Endod J 2001; 34: 40-6.

[6] Anusavice K. Phillips’ Science of Dental Materials. 11 th ed. Saunders. 2003; 464.

[7] Arunpraditkul S, Saengsanon S, Pakviwat W. Fracture resistance of endodontically treated teeth: three walls versus four walls of remaining coronal tooth structure. J Prosthodont 2009; 18: 49-53.

[8] Asmussen E, Peutzfeldt A, Heitmann T. Stiffness, elastic limit, and strength of newer types of endodontic posts. J Dent 1999; 27: 275-8.

[9] Assif D, Bitenski A, Pilo R, Oren E. Effect of post design on resistance to fracture of endodontically treated teeth with complete crowns. J Prosthet Dent 1993; 69: 36-40.

[10] Assif D, Ferber A. Retention of dowels using a composite resin as a cementing medium. J Prosthet Dent 1982; 48: 292-6.

[11] Assif D, Gorfil C. Biomechanical considerations in restoring endodontically treated teeth. J Prosthet Dent 1994; 71: 565-7.

[12] Assif D, Nissan J, Gafni Y, Gordon M. Assessment of the resistance to fracture of endodontically treated molars restored with amalgam. J Prosthet Dent 2003; 89: 462-5.

[13] Aykent F, Kalkan M, Yucel MT, Ozyesil AG. Effect of dentin bonding and ferrule preparation on the fracture strength of crowned teeth restored with dowels and amalgam cores. J Prosthet Dent 2006; 95: 297-301.

[14] Bachicha WS, DiFiore PM, Miller DA, Lautenschlager EP, Pashley DH. Microleakage of endodontically treated teeth restored with posts. J Endod 1998; 24: 703-8.

[15] Balbosh A, Kern M. Effect of surface treatment on retention of glass-fiber endodontic posts. J Prosthet Dent 2006; 95: 218-23.

[16] Balbosh A, Ludwig K, Kern M. Comparison of titanium dowel retention using four different luting agents. J Prosthet Dent 2005; 94: 227-33.

[17] Baraban DJ. The restoration of pulpless teeth. Dent Clin North Am 1967: 633-53.

[18] Baratieri LN, De Andrada MA, Arcari GM, Ritter AV. Influence of post placement in the fracture resistance of endodontically treated incisors veneered with direct composite. J Prosthet Dent 2000; 84: 180-4.

[19] Barkhordar RA, Radke R, Abbasi J. Effect of metal collars on resistance of endodontically treated teeth to root fracture. J Prosthet Dent 1989; 61: 676-8.

[20] Bateli M, Kern M, Wolkewitz M, Strub JR, Att W. A retrospective evaluation of teeth restored with zirconia ceramic posts: 10-year results. Clin Oral Investig 2014, in press. DOI: 10.1007/s00784-013-1065-5

[21] Bayindir F, Akyil MS, Bayindir YZ. Effect of eugenol and non-eugenol containing temporary cement on permanent cement retention and microhardness of cured composite resin. Dent Mater J 2003; 22: 592-9.

[22] Bergman B, Lundquist P, Sjogren U, Sundquist G. Restorative and endodontic results after treatment with cast posts and cores. J Prosthet Dent 1989; 61: 10-5.

[23] Bitter K, Noetzel J, Stamm O, Vaudt J, Meyer-Lueckel H, Neumann K, Kielbassa AM. Randomized clinical trial comparing the effects of post placement on failure rate of postendodontic restorations: preliminary results of a mean period of 32 months. J Endod 2009; 35: 1477-82.

[24] Carter JM, Sorensen SE, Johnson RR, Teitelbaum RL, Levine MS. Punch shear testing of extracted vital and endodontically treated teeth. J Biomech 1983; 16: 841-8.

[25] Chang WC, Millstein PL. Effect of design of prefabricated post heads on core materials. J Prosthet Dent 1993; 69: 475-82.

[26] Cheron RA, Marshall SJ, Goodis HE, Peters OA. Nanomechanical properties of endodontically treated teeth. J Endod 2011; 37: 1562-5.

[27] Cormier CJ, Burns DR, Moon P. In vitro comparison of the fracture resistance and failure mode of fiber, ceramic, and conventional post systems at various stages of restoration. J Prosthodont 2001; 10: 26-36.

[28] Craig RG. Restorative dental materials. 13th ed. St Louis: Mosby. 2012; 41, 340.

[29] Creugers NH, Mentink AG, Fokkinga WA, Kreulen CM. 5-year follow-up of a prospective clinical study on various types of core restorations. Int J Prosthodont 2005; 18: 34-9.

[30] Creugers NH, Mentink AG, Kayser AF. An analysis of durability data on post and core restorations. J Dent 1993; 21: 281-4.

[31] Dejak B, Mlotkowski A. The influence of ferrule effect and length of cast and FRC posts on the stresses in anterior teeth. Dent Mater 2013; 29: e227-37.

[32] DeLong R, Douglas WH. Development of an artificial oral environment for the testing of dental restoratives: bi-axial force and movement control. J Dent Res 1983; 62: 32-6.

[33] Dietschi D, Duc O, Krejci I, Sadan A. Biomechanical considerations for the restoration of endodontically treated teeth: a systematic review of the literature, Part II (Evaluation of fatigue behavior, interfaces, and in vivo studies). Quintessence Int 2008; 39: 117-29.

[34] Dietschi D, Duc O, Krejci I, Sadan A. Biomechanical considerations for the restoration of endodontically treated teeth: a systematic review of the literature--Part 1. Composition and micro- and macrostructure alterations. Quintessence Int 2007; 38: 733-43.

[35] El Guindy J, Fouda MY. Effect of obturating systems, dowel materials, and adhesive luting techniques on the resistance to fracture of endodontically treated teeth. J Prosthodont 2010; 19: 544-52.

[36] Fernandes AS, Dessai GS. Factors affecting the fracture resistance of post-core reconstructed teeth: a review. Int J Prosthodont 2001; 14: 355-63.

[37] Ferrari M, Vichi A, Garcia-Godoy F. Clinical evaluation of fiber-reinforced epoxy resin posts and cast post and cores. Am J Dent 2000; 13: 15B-8B.

[38] Fokkinga WA, Kreulen CM, Bronkhorst EM, Creugers NH. Up to 17-year controlled clinical study on post-and-cores and covering crowns. J Dent 2007; 35: 778-86.

[39] Fokkinga WA, Kreulen CM, Vallittu PK, Creugers NH. A structured analysis of in vitro failure loads and failure modes of fiber, metal, and ceramic post-and-core systems. Int J Prosthodont 2004; 17: 476-82.

[40] Gateau P, Sabek M, Dailey B. Fatigue testing and microscopic evaluation of post and core restorations under artificial crowns. J Prosthet Dent 1999; 82: 341-7.

[41] Goerig AC, Mueninghoff LA. Management of the endodontically treated tooth. Part I: concept for restorative designs. J Prosthet Dent 1983; 49: 340-5.

[42] Goga R, Purton DG. The use of endodontically treated teeth as abutments for crowns, fixed partial dentures, or removable partial dentures: a literature review. Quintessence Int 2007; 38: e106-11.

[43] Grieznis L, Apse P, Soboleva U. The effect of 2 different diameter cast posts on tooth root fracture resistance in vitro. Stomatologija 2006; 8: 30-2.

[44] Guzy GE, Nicholls JI. In vitro comparison of intact endodontically treated teeth with and without endo-post reinforcement. J Prosthet Dent 1979; 42: 39-44.

[45] Helfer AR, Melnick S, Schilder H. Determination of the moisture content of vital and pulpless teeth. Oral Surg Oral Med Oral Pathol 1972; 34: 661-70.

[46] Hemmings KW, King PA, Setchell DJ. Resistance to torsional forces of various post and core designs. J Prosthet Dent 1991; 66: 325-9.

[47] Hikasa T, Matsuka Y, Mine A, Minakuchi H, Hara ES, Van Meerbeek B, Yatani H, Kuboki T. A 15-year clinical comparative study of the cumulative survival rate of cast metal core and resin core restorations luted with adhesive resin cement. Int J Prosthodont 2010; 23: 397-405.

[48] Holmes DC, Diaz-Arnold AM, Leary JM. Influence of post dimension on stress distribution in dentin. J Prosthet Dent 1996; 75: 140-7.

[49] Huang TJ, Schilder H, Nathanson D. Effects of moisture content and endodontic treatment on some mechanical properties of human dentin. J Endod 1992; 18: 209-15.

[50] Isidor F, Brondum K, Ravnholt G. The influence of post length and crown ferrule length on the resistance to cyclic loading of bovine teeth with prefabricated titanium posts. Int J Prosthodont 1999; 12: 78-82.

[51] Isidor F, Odman P, Brondum K. Intermittent loading of teeth restored using prefabricated carbon fiber posts. Int J Prosthodont 1996; 9: 131-6.

[52] Jacoby WE, Jr. Practical technique for the fabrication of a direct pattern for a post-core restoration. J Prosthet Dent 1976; 35: 357-60.

[53] Jokstad A, Mjor IA. Ten years' clinical evaluation of three luting cements. J Dent 1996; 24: 309-15.

[54] Juloski J, Radovic I, Goracci C, Vulicevic ZR, Ferrari M. Ferrule effect: a literature review. J Endod 2012; 38: 11-9.

[55] Junge T, Nicholls JI, Phillips KM, Libman WJ. Load fatigue of compromised teeth: a comparison of 3 luting cements. Int J Prosthodont 1998; 11: 558-64.

[56] Kantor ME, Pines MS. A comparative study of restorative techniques for pulpless teeth. J Prosthet Dent 1977; 38: 405-12.

[57] Kugel G, Ferrari M. The science of bonding: from first to sixth generation. J Am Dent Assoc 2000; 131 Suppl: 20S-5S.

[58] Larato DC. Single unit cast post crown for pulpless anterior tooth roots. The Journal of Prosthetic Dentistry 1966; 16: 145-9.

[59] Lassila LV, Tanner J, Le Bell AM, Narva K, Vallittu PK. Flexural properties of fiber reinforced root canal posts. Dent Mater 2004; 20: 29-36.

[60] Libman WJ, Nicholls JI. Load fatigue of teeth restored with cast posts and cores and complete crowns. Int J Prosthodont 1995; 8: 155-61.

[61] Lovdahl PE, Nicholls JI. Pin-retained amalgam cores vs. cast-gold dowel-cores. J Prosthet Dent 1977; 38: 507-14.

[62] Maccari PC, Conceicao EN, Nunes MF. Fracture resistance of endodontically treated teeth restored with three different prefabricated esthetic posts. J Esthet Restor Dent 2003; 15: 25-30; discussion 1.

[63] Mangold JT, Kern M. Influence of glass-fiber posts on the fracture resistance and failure pattern of endodontically treated premolars with

varying substance loss: an in vitro study. J Prosthet Dent 2011; 105: 387-93.

[64] Mannocci F, Qualtrough AJ, Worthington HV, Watson TF, Pitt Ford TR. Randomized clinical comparison of endodontically treated teeth restored with amalgam or with fiber posts and resin composite: five-year results. Oper Dent 2005; 30: 9-15.

[65] Marchan S, Coldero L, Whiting R, Barclay S. In vitro evaluation of the retention of zirconia-based ceramic posts luted with glass ionomer and resin cements. Braz Dent J 2005; 16: 213-7.

[66] McDonald AV, King PA, Setchell DJ. In vitro study to compare impact fracture resistance of intact root-treated teeth. Int Endod J 1990; 23: 304-12.

[67] Mendoza DB, Eakle WS. Retention of posts cemented with various dentinal bonding cements. J Prosthet Dent 1994; 72: 591-4.

[68] Mendoza DB, Eakle WS, Kahl EA, Ho R. Root reinforcement with a resin-bonded preformed post. J Prosthet Dent 1997; 78: 10-4.

[69] Meng QF, Chen YM, Guang HB, Yip KH, Smales RJ. Effect of a ferrule and increased clinical crown length on the in vitro fracture resistance of premolars restored using two dowel-and-core systems. Oper Dent 2007; 32: 595-601.

[70] Millstein PL, Nathanson D. Effect of eugenol and eugenol cements on cured composite resin. J Prosthet Dent 1983; 50: 211-5.

[71] Monticelli F, Grandini S, Goracci C, Ferrari M. Clinical behavior of translucent-fiber posts: a 2-year prospective study. Int J Prosthodont 2003; 16: 593-6.

[72] Morgano SM, Brackett SE. Foundation restorations in fixed prosthodontics: current knowledge and future needs. J Prosthet Dent 1999; 82: 643-57.

[73] Morgano SM, Milot P. Clinical success of cast metal posts and cores. J Prosthet Dent 1993; 70: 11-6.

[74] Naumann M, Koelpin M, Beuer F, Meyer-Lueckel H. 10-year survival evaluation for glass-fiber-supported postendodontic restoration: a prospective observational clinical study. J Endod 2012; 38: 432-5.

[75] Naumann M, Preuss A, Rosentritt M. Effect of incomplete crown ferrules on load capacity of endodontically treated maxillary incisors restored with fiber posts, composite build-ups, and all-ceramic crowns: an in vitro evaluation after chewing simulation. Acta Odontol Scand 2006; 64: 31-6.

[76] O'Keefe KL, Miller BH, Powers JM. In vitro tensile bond strength of adhesive cements to new post materials. Int J Prosthodont 2000; 13: 47-51.

[77] Pegoretti A, Fambri L, Zappini G, Bianchetti M. Finite element analysis of a glass fibre reinforced composite endodontic post. Biomaterials 2002; 23: 2667-82.

[78] Pereira JR, de Ornelas F, Conti PC, do Valle AL. Effect of a crown ferrule on the fracture resistance of endodontically treated teeth restored with prefabricated posts. J Prosthet Dent 2006; 95: 50-4.

[79] Perel ML, Muroff FI. Clinical criteria for posts and cores. J Prosthet Dent 1972; 28: 405-11.

[80] Peroz I, Blankenstein F, Lange KP, Naumann M. Restoring endodontically treated teeth with posts and cores--a review. Quintessence Int 2005; 36: 737-46.

[81] Peters MC, Poort HW, Farah JW, Craig RG. Stress analysis of a tooth restored with a post and core. J Dent Res 1983; 62: 760-3.

[82] Pilo R, Cardash HS, Levin E, Assif D. Effect of core stiffness on the in vitro fracture of crowned, endodontically treated teeth. J Prosthet Dent 2002; 88: 302-6.

[83] Randow K, Glantz PO. On cantilever loading of vital and non-vital teeth. An experimental clinical study. Acta Odontol Scand 1986; 44: 271-7.

[84] Reeh ES, Messer HH, Douglas WH. Reduction in tooth stiffness as a result of endodontic and restorative procedures. J Endod 1989; 15: 512-6.

[85] Rivera EM, Yamauchi M. Site comparisons of dentine collagen cross-links from extracted human teeth. Arch Oral Biol 1993; 38: 541-6.

[86] Robbins JW. Guidelines for the restoration of endodontically treated teeth. J Am Dent Assoc 1990; 120: 558, 60, 62 passim.

[87] Robbins JW, Earnest LA, Schumann SD. Fracture resistance of endodontically-treated cuspids. Am J Dent 1993; 6: 159-61.

[88] Rosenstiel SF, Land MF, Crispin BJ. Dental luting agents: A review of the current literature. J Prosthet Dent 1998; 80: 280-301.

[89] Sadek FT, Monticelli F, Goracci C, Tay FR, Cardoso PE, Ferrari M. Bond strength performance of different resin composites used as core materials around fiber posts. Dent Mater 2007; 23: 95-9.

[90] Sakaguchi RL, Douglas WH, DeLong R, Pintado MR. The wear of a posterior composite in an artificial mouth: a clinical correlation. Dent Mater 1986; 2: 235-40.

[91] Salameh Z, Sorrentino R, Ounsi HF, Goracci C, Tashkandi E, Tay FR, Ferrari M. Effect of different all-ceramic crown system on fracture resistance and failure pattern of endodontically treated maxillary premolars restored with and without glass fiber posts. J Endod 2007; 33: 848-51.

[92] Salameh Z, Sorrentino R, Papacchini F, Ounsi HF, Tashkandi E, Goracci C, Ferrari M. Fracture resistance and failure patterns of endodontically treated mandibular molars restored using resin composite with or without translucent glass fiber posts. J Endod 2006; 32: 752-5.

[93] Schmitter M, Hamadi K, Rammelsberg P. Survival of two post systems--five-year results of a randomized clinical trial. Quintessence Int 2011; 42: 843-50.

[94] Schwartz RS, Robbins JW. Post placement and restoration of endodontically treated teeth: a literature review. J Endod 2004; 30: 289-301.

[95] Sedgley CM, Messer HH. Are endodontically treated teeth more brittle? J Endod 1992; 18: 332-5.

[96] Sherfudhin H, Hobeich J, Carvalho CA, Aboushelib MN, Sadig W, Salameh Z. Effect of different ferrule designs on the fracture resistance and failure pattern of endodontically treated teeth restored with fiber posts and all-ceramic crowns. J Appl Oral Sci 2011; 19: 28-33.

[97] Sorensen JA, Engelman MJ. Effect of post adaptation on fracture resistance of endodontically treated teeth. J Prosthet Dent 1990; 64: 419-24.

[98] Sorensen JA, Engelman MJ. Ferrule design and fracture resistance of endodontically treated teeth. J Prosthet Dent 1990; 63: 529-36.

[99] Sorensen JA, Martinoff JT. Intracoronal reinforcement and coronal coverage: a study of endodontically treated teeth. J Prosthet Dent 1984; 51: 780-4.

[100] Standlee J, Caputo A. Biomechanics. J Calif Dent Assoc 1988; 16: 49-58.

[101] Standlee JP, Caputo AA, Hanson EC. Retention of endodontic dowels: effects of cement, dowel length, diameter, and design. J Prosthet Dent 1978; 39: 400-5.

[102] Stankiewicz N, Wilson P. The ferrule effect. Dent Update 2008; 35: 222-4, 7-8.

[103] Steiner M, Mitsias ME, Ludwig K, Kern M. In vitro evaluation of a mechanical testing chewing simulator. Dent Mater 2009; 25: 494-9.

[104] Stern N, Hirshfeld Z. Principles of preparing endodontically treated teeth for dowel and core restorations. J Prosthet Dent 1973; 30: 162-5.

[105] Stockton LW. Factors affecting retention of post systems: a literature review. J Prosthet Dent 1999; 81: 380-5.

[106] Tan PL, Aquilino SA, Gratton DG, Stanford CM, Tan SC, Johnson WT, Dawson D. In vitro fracture resistance of endodontically treated central incisors with varying ferrule heights and configurations. J Prosthet Dent 2005; 93: 331-6.

[107] Theodosopoulou JN, Chochlidakis KM. A systematic review of dowel (post) and core materials and systems. J Prosthodont 2009; 18: 464-72.

[108] Tjan AH, Dunn JR, Lee JK. Fracture resistance of amalgam and composite resin cores retained by various intradentinal retentive features. Quintessence Int 1993; 24: 211-7.

[109] Torbjorner A, Fransson B. A literature review on the prosthetic treatment of structurally compromised teeth. Int J Prosthodont 2004; 17: 369-76.

[110] Torbjorner A, Karlsson S, Odman PA. Survival rate and failure characteristics for two post designs. J Prosthet Dent 1995; 73: 439-44.

[111] Trabert KC, Caput AA, Abou-Rass M. Tooth fracture--a comparison of endodontic and restorative treatments. J Endod 1978; 4: 341-5.

[112] Trabert KC, Cooney JP. The endodontically treated tooth. Restorative concepts and techniques. Dent Clin North Am 1984; 28: 923-51.

[113] Trope M, Maltz DO, Tronstad L. Resistance to fracture of restored endodontically treated teeth. Endod Dent Traumatol 1985; 1: 108-11.

[114] Vire DE. Failure of endodontically treated teeth: classification and evaluation. J Endod 1991; 17: 338-42.

[115] Wrbas KT, Schirrmeister JF, Altenburger MJ, Agrafioti A, Hellwig E. Bond strength between fibre posts and composite resin cores: effect of post surface silanization. Int Endod J 2007; 40: 538-43.

[116] Yaman P, Thorsteinsson TS. Effect of core materials on stress distribution of posts. J Prosthet Dent 1992; 68: 416-20.

[117] Zhi-Yue L, Yu-Xing Z. Effects of post-core design and ferrule on fracture resistance of endodontically treated maxillary central incisors. J Prosthet Dent 2003; 89: 368-73.

[118] Zicari F, Van Meerbeek B, Scotti R, Naert I. Effect of ferrule and post placement on fracture resistance of endodontically treated teeth after fatigue loading. J Dent 2013; 41: 207-15.

9. ACKNOWLEDGMENTS

I am very thankful to all of my committee members for making this thesis possible. Sincere thanks are extended to Prof. Dr. Matthias Kern, chairman of Prosthodontics, Propaedeutic and Materials Science Department, who was always willing to listen, talk, and give positive feedback with continued support to complete this research project.

I am deeply thankful to my dear friend Dr. Shadi El Bahra for his continuous help in this study.

I am grateful to Dr. Sandra Freitag-Wolf, Institute of Medical Informatics and Statistics, University of Kiel, for her help in compiling the statistics in this study.

I would also like to thank the companies Brasseler and Kuraray for supplying me with the necessary materials and equipment to carry out my project.

10. DEDICATION

Finally, I dedicate this thesis to:

My Prophet Mohammed ……….…………….Peace be upon him

My parents ……………………………………. Ahmed and Wala'a

My wife …………………….…………….……………. Nedhal

My brothers ……………….….……………Mohammed and Ali

My sisters ……………………...Gaitha, 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

Name	Abdulaziz Samran	
Nationality	Yemeni	
Date & place of birth	Yemen, Al-baidha 18.12.1978	
Address	Brunswikerstr. 30 24105 Kiel	
E-mail	asamran@proth.uni-kiel.de aasamran@gmail.com	
Sex	Male	
Tel	017647025702	

ACADEMIC BACK GROUND:

- Current position: visiting researcher in Christian-Albrechts University to Kiel, Faculty of Medicine, Dept. of Prosthodontics, Propaedeutics, and Dental Materials.

- Master in Fixed Prosthodontics (2010), Aleppo University, Faculty of dentistry (Syria).

- Bachelor's Degree in Dentistry (2001-2002), Aleppo University, Faculty of dentistry (Syria).

EXPERIENCES AND SKILLS:

- A member of teaching staff in Ibb University, Faculty of dentistry (Yemen) Dept. of Fixed Prosthodontics.
- A member of teaching staff in Al-Farabi Dental College, Faculty of dentistry (Saudi Arabia), Dept. Restorative Dental Sciences.

PERSONAL SKILS:

- Very good in general relationship establishment.
- High ability to work with many people (team-work).

MEMBERS AND ORGANIZATIONS:

- Yemen Dental Association
- Saudi Dental Society

COURSES:

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

LANGUAGES:

- 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