An *In Vitro* Study of the Influence of Remaining Coronal Tooth Structure on the Fracture Resistance of Endodontically-Treated Maxillary Premolars

A Thesis submitted in partial fulfillment of the requirements for the degree of
Doctor of Clinical Dentistry

Amal Mamdouh Bakey Rizk Ibrahim
BDSc, MDSc, ADC

School of Dentistry
The University of Adelaide

October 2012

This thesis is dedicated to my family:

My late father

He always encouraged and inspired me. Without him I wouldn’t have ever achieved what I did.

My husband; Ehab and my lovely kids; Karim and Sandra

They are always there cheering me up and stood by me through the good times and bad.

My mother and my sister

They are always supporting me with their best wishes.

TABLE OF CONTENTS

DECLARATION

I, Amal Ibrahim declare that this work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the university library, being made available for loan and photocopying, subject to the provisions of the copyright Act 1968.

I also give permission for the digital version of my thesis to be made available on the web, via the university's digital research repository, the library catalogue, and also the through web search engines, unless permission has been granted by the university to restrict access for period of time.

Amal Mamdouh Bakey Rizk Ibrahim

Date:

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to:

- My Supervisor ***Professor Lindsay Richards*** who supported me with his wise and thoughtful advice throughout my thesis. I greatly appreciate his precious time he offered to give me a hand whenever I was in need. This work was not possible without him.
- ***Dr Thomas Berekally*** for his precious time he gave to read this thesis and his critical comments about it. For his encouragement and support throughout my three years course.
- ***Associate Professor James Dudley*** for his valuable advice and guidance in the clinic.
- ***Dr Siobhan Gannon*** for her help in editing this thesis.
- ***Mr Victor Marino*** for the amount of effort he gave in samples preparation.
- ***Mr Greg Hamlyn, Mr Simon Jackson, and Mr Greg Natt;*** for their great help, material, equipment and technical support with crowns fabrications.
- ***My Postgraduate colleagues;*** Dr Zainab Hamudi, Dr My Ann Vu, Dr Sofie Bui, Dr Michael Zaninovich, Dr Ying Guo, Dr Jonathan Innes and Dr Benjamin Sellick for their wonderful friendship. It has been a great pleasure to know you all.

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Objectives: This *in vitro* study investigated the relationship between the cross-sectional area and the location of remaining coronal tooth structure and the fracture resistance of restored endodontically-treated teeth.

Materials and Methods: Fifty-five extracted maxillary premolars received root canal treatment and crown preparation and were randomly divided into 11 groups of five teeth each according to the number and the site of the missing axial wall(s). Impressions of the prepared teeth were taken and poured with epoxy resin to construct a die for each tooth that was then sectioned 1mm above the finish line. The surface area was measured using ImageJ software (version 1.41n. Developed by Wayne Rasband. National Institutes of Health, USA.[1] All 55 prepared teeth were then restored with composite resin cores, and cast metal crowns. Specimens were thermocycled between 5°C and 55°C for 500 cycles, prior to testing. A universal testing machine was used to apply a compressive load at a crosshead speed of 1mm/min to the palatal surface of the buccal cusp of the crown at an angle of 45 degrees to the long axis of the tooth until failure. Results were analyzed using one-way ANOVA and t-tests.

Results: Specimens with all axial walls intact (only access cavity) had mean fracture strength of 1380.5±393.9N. Groups that have a missing palatal wall with one or two proximal walls showed the lowest mean failure loads of 398.4N ± 149.5N and 344.7N ±

91.2N respectively. The coefficient of determination (R^2) between the surface area and the fracture resistance was 0.52.

Conclusions: For restored endodontically-treated upper premolars there is a positive linear relationship between the remaining dentine surface area and fracture strength. Residual dentine location influences the fracture resistance with the palatal wall having a major role in resisting force.

INTRODUCTION

The restoration of endodontically-treated teeth involves a variety of treatment options and still represents a challenging task for clinicians.[2] It is well accepted that root canal treated teeth with an extensive loss of tooth structure have a significantly reduced capacity to resist functional forces.[3] Accordingly the residual coronal dentine must be carefully assessed before a decision is made regarding its restorability with a direct core buildup or a post and core.

It is widely accepted that the prognosis for the tooth correlates with the amount of remaining tooth structure,[4] however this subject has never been clinically investigated. The inability to retrospectively determine the amount of lost tooth structure necessitates a precise and simple specification of the condition of the tooth before restoring it. A previous study[5] showed that the coronal aspect of the remaining hard tissue as well as the thickness of the wall of the coronal part of the root is important.

Tjan and Whang[6] concluded that a 2-mm thickness of dentine would improve resistance to the fracture of root-treated teeth, while other authors[7, 8] recommended approximately 2 mm of coronal tooth structure as an ideal height. Ferrules have been widely studied and their recommended lengths vary from 1.5 to 2.5mm. The extent to which dentine preservation has an effect on the success of the endodontically-treated teeth remains unclear. For example in several studies[6, 92-95] the height was assessed with no particular focus on the thickness of remaining coronal tooth structure. Tooth resistance is not improved by a ferrule when thin root canal walls of excessively flared teeth are present.[9] The required thickness and strategic preservation of dentine is still unknown.

In addition, most clinical studies or treatment recommendations describe tooth destruction in arbitrary terms such as 'more than half the coronal tooth structure', 'loss of more than 50%' or 'badly broken teeth', which leaves room for a wide range of interpretation. Although clinicians generally believe that there is a strong association between remaining tooth structure and the survival of root canal-treated teeth. There is a paucity of data to support this. Therefore, there is a need to quantify remaining tooth structure and relate it to the fracture resistance of the tooth, and its clinical prognosis.

REVIEW OF LITERATURE

The failure of endodontically-treated teeth is a significant clinical problem which has been investigated using a range of laboratory, mathematical and clinical protocols each of which have advantages and limitations.

2.1 *In vitro* testing of teeth

In vitro testing provides an opportunity to control the variables that are likely to influence fracture strength. Some of these relate to the experimental system e.g. storage media, thermocycling protocol, mounting and periodontium simulation and others relate to the loading protocol.

2.1.1 Effect of storage media on the strength

The effects of storage on the biomechanical testing of dentine have not been extensively reported. Some studies[10, 11] used a thymol solution because it is an antifungal agent. Carter *et al*[12] found that different storage media (tap water or mineral oil) did not affect shear strength and toughness of the tested teeth but that dry storage can be a significant factor. Dehydration of human dentine does not appear to weaken dentine structure in terms of strength and toughness, but it tends to increase the stiffness and decrease the flexibility of dentine for both normal and treated pulpless tooth samples.[13]

2.1.2 Thermocycling protocol

Teeth are subjected to significant temperature changes during intake of food and drinks of various temperatures. Because of the different thermal expansion of enamel and dentine, temperature differences can cause modifications to the tooth structure.[14] Temperature changes can cause thermal stresses, which are proportional to the temperature difference, the tooth experiences. With sufficient repeated high or low thermal stress, the tooth structure may be damaged.[15] Exposure of restorations in extracted teeth to cyclic thermal fluctuations to simulate one of the many factors in the oral environment has been common in many laboratory tests.

Temperature changes used have rarely been substantiated with temperature measurements made *in vivo* and vary considerably between reports. A review by Gale and Darvell[16] assessed reports describing temperature changes of teeth *in vivo* and analyzed 130 studies of laboratory thermal cycling of teeth selected from 25 journals. They found that variation of regimens used was large, making comparison difficult. Reports of testing the effects of thermal cycling were not consistent, but generally leakage increased with thermal stress, although the evidence linking cyclic testing to clinical failures is weak and the number of cycles likely to be experienced *in vivo* is uncertain but a provisional estimate of approximately 10,000 cycles per year was suggested.[16]

Ernst *et al*[14] examined the validity of the ISO standards for thermoccycling (500 thermal cycles at 5°C and 55°C) and found that the actual thermal stress in the interproximal space of teeth is slightly lower than the one used in *in vitro* examinations and temperature stress limits selected at 5-55 degrees cover the actually occurring temperature interval quite well. Therefore the temperature range used widely for the *in vitro* testing of dental materials seems to "overstress" the interface to a certain extent, which seems preferable to an "under-stressed" situation.[14]

2.1.3 Mounting samples for testing

Some studies mount the teeth in metal,[17, 18, 19] or plastic[20, 21] rings with the roots embedded at or up to 2mm below the cementoenamel junction using self-cure acrylic.[22, 23]

The temperature rise involved in embedding extracted teeth in acrylic resin can be high. Loney *et al* [24] measured a rise of 48°C above room temperature while embedding samples in acrylic resin without coolant. Although the effect of such a rise in temperature on the integrity of teeth was not measured, they suggested that thermal expansion of the teeth can cause crazing, fracture, or weakening of the samples.

2.1.4 Periodontium simulation

It has been shown that the presence of a periodontal analogue is important in fracture testing, resulting in significant modifications in modes of fracture[25]. Teeth mounted without a ligament tended to fracture either at the cementoenamel junction or through the crown, whereas teeth mounted with ligaments fractured at or apical to the cementoenamel junction.

To simulate a human periodontium, the roots of the teeth are covered with a 0.1-mm- thick layer of autopolymerizing silicone.[22, 23, 26, 27] Other studies[28, 29] wrapped the root portion below the CEJ of the specimen twice with poly-tetra-fluoro-ethylene tape to simulate the 0.2-mm thickness of the periodontal ligament. The material used for periodontal ligament (PL) simulation was not found to be significant.[25]

A more complex method was suggested by Soares *et al*[25] in which root surfaces were dipped into molten wax to form a 0.2- to 0.3-mm- thick layer. The teeth were stabilized using a radiographic film with a central circular hole. Then, a plastic cylinder was placed over the root and fixed in position. The cylinder was then filled with the resin. After resin polymerization, the teeth were removed from the cylinder and the wax was removed from the both root surface and resin cylinder. Polyether material was placed in the resin cylinder, the tooth was inserted in the cylinder, and the excess polyether material was removed with a scalpel blade.[25, 30]

2.1.4 Type of load

The fracture resistance of teeth is used in many studies, whilst it is the simplest to perform, it is a destructive test that may not always simulate *in vivo* conditions, as the forces required to fracture specimens *in vitro* may not occur in the oral cavity.[20, 31-33]

In a study by Fennis *et al*,[34] mastication was reported as the most frequent cause of complete cusp fracture. While the application of static force does not necessarily simulate actual intraoral loading,[35] the general hypothesis is that it would at least detect differences between treatment modalities with regard to strength.[36] However the clinical loading of teeth is a dynamic process, in which loading force, frequency and direction vary greatly.[37] Also, in the mouth, repeated loading can lead to fatigue failure, so the interpretation of results should be done with caution.

A variety of crosshead speeds, commonly in the range of 1mm/min[19, 38] or 2mm/min,[39] have been used by different researchers, but this does not seem to be a critical factor.[11] Espevik[40] stated that lower speeds are accompanied by greater plastic deformation as a result of which higher fracture resistance measurements will be recorded.

2.1.6 Direction of load

The direction of forces on the tooth cusps during various excursive jaw movements is complex, and is influenced by different factors such as cuspal morphology and intermaxillary occlusal relationships. The direction of load may affect the fracture resistance of teeth. Loney *et al* [24] demonstrated significant differences in fracture resistance of maxillary central incisor between specimens tested at the different load angles (110, 130, 150 degrees). Mean failure loads increased, as the load angle became more parallel to the long axis of the teeth.[24]

Clinically, occlusal loads are considerably more complex, both in terms of angulation and point of application.[41] Consequently, the use of a single load angle in laboratory studies is an inherent experimental flaw.

The direction of loads used in testing premolar teeth varies in reported studies and includes being applied to: the triangular ridge of the functional cusp;[21, 42] the supporting cusp;[28, 32, 39] or to the center of the occlusal surface in contact with both cusp inclines parallel to the long axis of the tooth.[31, 42, 43]

Clinically it is rare that the cusps will fracture in an intact tooth.[44] Only a sudden blow, such as chewing hard objects may cause cuspal fracture. On the other hand weak cusps further weakened by caries and/or restorations will have a greater tendency to fracture.[44]

Teeth are most vulnerable to fracture when eccentric forces are applied. Different angles of loading had been used varying between 30 degrees,[18, 39, 42] 45 degrees [28, 32] and parallel to the long axis of the tooth.[27, 31, 42]

Vertical forces are better tolerated because they are directed against the dense bone around the apex of the tooth, while lateral forces are more destructive as they are directed against the thinner and weaker buccal, lingual and interproximal walls of the alveolus.[45]

Several laboratory studies used different loading elements such as rods,[28, 32] wedges[46] and balls, [18, 31, 42] resulting in different values of the load to fracture.

2.2 Computer simulation studies

Finite element analysis (FEA) is a method that models stress distribution within complex structures.[47] These models are specific for the input design and parameters without any influence from biological variables. The accuracy of the results depends on how close the model is to reality.[47, 48] Because of the large variability in the results obtained from *in vitro* studies, different questions related to the ferrule effect have been investigated based on FEA.[49, 50]

One study[48] aimed to combine the advantages of *in vitro* tests and FEA. In order to evaluate distribution of the external forces among different internal substructures, virtual models of intact teeth and models of teeth with different damage levels were investigated. The results obtained from both methods were compared with a high level of agreement.

Based on studies of this type, authors have suggested that the ferrule height should be determined individually according to the buccolinual cervical diameter of the tooth.

2.3 Clinical trials

Many *in vivo* studies evaluating the clinical longevity of root-treated teeth have been retrospective in nature and therefore do not include information on residual dentine. Moreover there is little prospective data to provide evidence-base guidelines for the restoration of the root canal-treated teeth.

The amount of tooth structure available for a ferrule calculated retrospectively from bitewing radiographs was not a significant preoperative predictor of the prognosis of restored endodontically-treated molars.[51] It was commented that judgment on a preexisting ferrule is difficult to obtain retrospectively and should be evaluated from a models or cone-beam tomography to obtain three-dimensional rather than two-dimensional information about the pre-restorative condition.

The effect of the remaining tooth structure on the survival of teeth restored with a cast post and core system, a direct metal post, or no post has also been studied[52]. The expected dentine height remaining after tooth preparation was categorized as substantial (a 1-mm or 2-mm ferrule could be achieved) or minimal (a ferrule could not be achieved). Over a 5-year follow-up period, teeth with a substantial dentine height performed significantly better than teeth with less remaining tooth structure, whereas the type of restoration did not have an influence.

Two studies[53, 54] evaluated the clinical behavior of endodontically-treated premolars with varying degrees of coronal tissue loss. The amount of dentine remaining at the coronal level was assessed before composite abutment buildup and crown preparation, depending on the height and thickness of the remaining dentine. All teeth were restored with porcelain fused to metal crown. Over a 2-[53] or 3-[54] year observation period, post placement appeared to significantly influence the survival of restored teeth. Nevertheless, irrespective of the restorative procedure, the preservation of at least one coronal wall significantly reduced the failure risk. When all coronal walls were missing, similar failure risks existed regardless of the presence or absence of 2-mm-high ferrule retention[53, 54]

Ferrari M. et al[55] in 2012 conducted a randomized controlled trial to examine the contribution of remaining coronal dentine and placement of a prefabricated or customized fiber post to the six-year survival of endodontically-treated premolars. The absence of a ferrule in a restored tooth showed a significantly higher risk of failure than when at least one coronal wall was retained.

2.4 Anatomy of upper premolars

Cavel *et al*.[56] suggested that "the tooth anatomy could be partially responsible for susceptibility to fracture, and tooth inclination could heighten it." Maxillary premolars have smaller functional cusps compared with non-functional cusps. They account for approximately 47% of the buccolingual dimension of the tooth, with a range of 46% to 48%.[44] The functional cusps have steeper inclines than the nonfunctional cusps which can be a contributing factor for the higher incidence of fracture of the functional cusps.[44]

Khera *et al*.[44] found that the enamel thickness in functional cusps in upper premolars is significantly greater than in nonfunctional cusps with a difference of 0.282 ± 0.129 mm. The difference in enamel thickness could be an important parameter in the protection of cusps.[44] Despite this difference in enamel thickness, maxillary premolars, can be more critically influenced by their size than by enamel thickness.[56] (Figures 1, 2 and 3)

In addition, loss of tooth structure during endodontic access and cavity preparation procedures make those premolars even weaker and more prone to fracture.[57] Clinically root canal-treated maxillary first premolars present a restorative challenge due to the loss of coronal tooth structure and the presence of radicular fluting, with 2 thin roots that limit the therapeutic options.[34] Endodontic treatment and post hole preparation were found to reduce more dentine in the bifurcation area of both roots compared to the outer aspect. Post space preparation usually compromises 61% of palatal and 77% of buccal roots,[58] leaving residual dentine thickness of less than the recommended minimum 1-mm thickness.

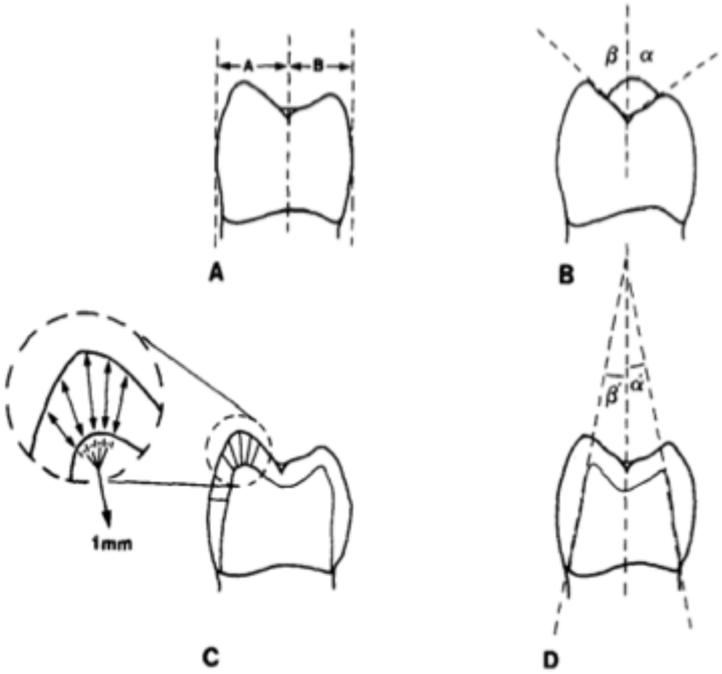


Figure 1: Diagram taken from Khera *et al*[44] showing difference between functional and non-functional cusps of upper premolars. (A) Buccolingual width, (B) cuspal inclination angle, (C) enamel thickness, and (D) angle of inclination of DEJ.

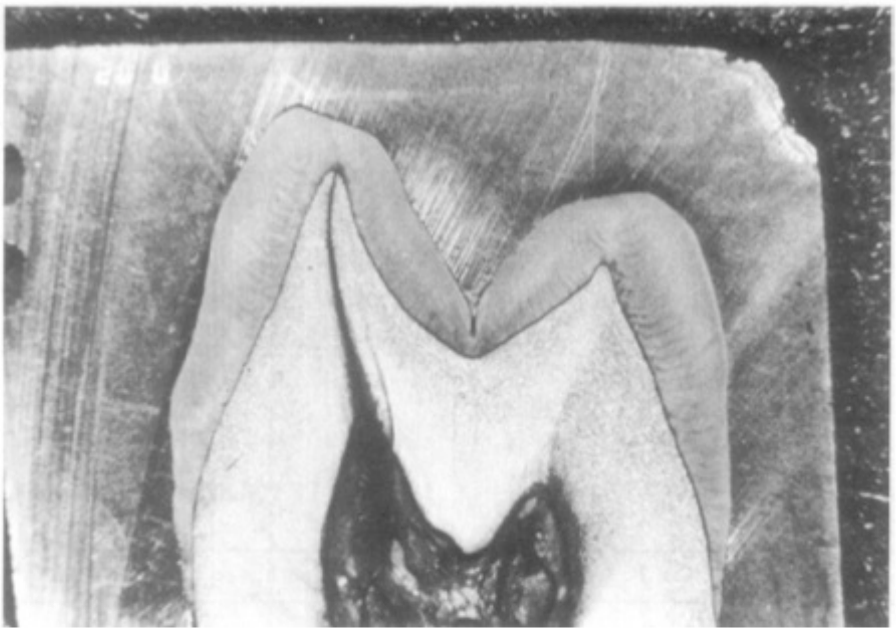


Figure 2: Photograph of maxillary premolar sectioned at buccal and lingual cusp tips. Functional cusp(Lingual on the right) is 44% of buccolingual width. Photograph taken from from Khera *et al.*[44]

Figure 3: Anatomy of upper premolar (Image taken from http://dentallecnotes.blogspot.com.au)

2.5 Causes of weakness of endodontically-treated teeth

Several classic studies have proposed that the dentine in endodontically-treated teeth is substantially different to dentine in teeth with "vital" pulps. It was thought that the dentine was more brittle because of water loss[59] and loss of collagen cross-linking[60] as a result of root canal treatment, leading to a consequent decrease in their resilience.[61] The supporting evidence for this is primarily a study by Helfer *et al*.[59] that showed 9% lower moisture content of pulpless compared with vital dog teeth. However this was not confirmed by later studies.[13, 62] In 1991, Huang *et al*.[13] compared the physical and mechanical properties of dentine 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 dentine.

Sedgley *et al* [63] compared different biomechanical properties including punch shear strength, toughness, hardness, and load to fracture of 23 endodontically-treated teeth and their contralateral vital pairs. The similarity between the contralateral pairs suggests that teeth do not become more brittle after endodontic treatment and other factors can be more critical to failure of endodontically-treated teeth.

According to Dietschi *et al,* [64] the loss of vitality and root canal treatment only affect the tooth biomechanical behavior to a limited extent. The tooth strength is reduced in proportion to coronal tissue lost, resulting from either carious lesions or restorative procedures. They found a direct relationship between the amount of remaining tooth structure and the ability to resist occlusal forces.[65]

The inherit elastic properties of intact enamel and dentine was found to be altered even when an occlusal cavity is prepared without endodontic access, leading to a reduction in fracture resistance.[66] Randow and Glantz[67] reported that after pulp extirpation teeth lose their protective bio-feedback mechanism and this may contribute to tooth fracture.

However, beside non-controllable risk factors for endodontically-treated teeth, the high occurrence of fractures may be attributed to various operative procedures, such as caries removal, access preparation, instrumentation of the root canal, irrigation of the canal with sodium hypochlorite,[68, 69] long-term intracanal dressings with calcium hydroxide,[70] obturation, post space preparation, and final coronal restoration,[64, 71] which lead to a loss of tooth structure or may weaken the dentine.

Higher fracture rates can be anticipated in endodontically-treated posterior teeth.[72] For example, it was reported in endodontically-treated maxillary premolars restored with a mesio-occluso-distal amalgam restoration, that nearly one third fractured within the first 3 years.[73] Fennis *et al*.[34] studied from insurance claims more than 46,000 patients and reported significantly more fractures in teeth with endodontic treatment. Statistical analysis revealed a positive correlation between history of endodontic treatment and subgingival fracture location.[34]

2.6 Effect of remaining tooth structure on the fracture resistance

Sound teeth rarely fracture under normal masticatory function. The potential of the endodontically-treated teeth to fracture increases proportionally with the amount of dentine removed. Therefore many studies[74-76] have emphasized the importance of preserving dental structure to maintain the strength of the remaining tooth. Generally, the wider the involvement by caries or cavity preparation, the weaker the tooth[31]. Fennis *et al* [34] looked at the incidence of complete cusp fractures of posterior teeth in Dutch general practices. The majority of fractured teeth were restored on three or more surfaces. The larger the restoration, the less tooth material and the weaker the tooth. There have been few studies on endodontically-treated premolars with only an occlusal access cavity prepared and intact marginal ridges. In order to gain entry to the root canal system, the endodontic access cavity cuts completely through enamel and dentine in an apical direction which significantly decreases the rigidity of the tooth.[77] This is opposite to the findings of Steele and Johnson[57] who found that an otherwise intact tooth with endodontic access cavity preparation had similar compressive fracture strength to that of an intact tooth.

Reeh *et al* [78] established that the loss of the marginal ridge integrity resulted in the greatest loss of stiffness. He showed that for premolar teeth the endodontic access cavity produced only a 5% decrease in stiffness, in contrast to an occlusal cavity preparation and MOD preparation, which decreased tooth stiffness by 20% and 63% respectively. These findings are supported by a study performed by Panitvisai *et al*.[79] These authors observed an increase in cuspal deflection with growing cavity size. This deflection might be increased if, in addition to the initial restoration, an access cavity had been prepared. Also, Caplan *et al*[80] found that teeth with two proximal contacts were three times less likely to be lost than teeth with one or no proximal contact.

Shahrbaf *et al* [21] evaluated the effect of varying marginal ridge thicknesses on the fracture resistance of endodontically-treated maxillary premolars restored with composite. They found that preserving a mesial marginal ridge with thicknesses of 2 mm, 1.5 mm and 1 mm in endodontically-treated and composite-restored maxillary premolars could help to preserve the fracture resistance of teeth. However, a 0.5 mm thickness of the mesial marginal ridge did not conserve the strength of restored teeth at the level of intact teeth but was greater than having no marginal ridge at all.

Nissan *et al* [39] assessed the resistance to fracture of crowned endodontically-treated maxillary first premolars under simulated occlusal load, while preserving various degrees of remaining coronal structure. They found that the remaining coronal structure was the major factor that influenced the fracture resistance, as there was increased protection against fracture under occlusal loads with more remaining tooth structure.

The issue of radicular dentine tissue (RDT) after root canal and dowel preparation is equally important. Excessive removal of radicular dentine can compromise the root. A direct relationship exists between the RDT and the strength of the root.[81] Post preparation not only weakens teeth,[82] but also affects the tooth's ability to withstand lateral stresses due to a decrease in the tooth wall thickness.[83] Thus, preservation of sound dentine is important. At least 1 mm of root dentine should remain in all root aspects along the entire length after completing all intra-radicular procedures to prevent root fracture under horizontally-directed force.[84, 85]

The thinner the root dentine, the more likely is the tooth to fracture. For mandibular incisors, finite element analysis (FEA) modeling of mid-root regions with circular canal diameters from 0.5–2.0 mm, and corresponding dentine wall thicknesses from 1.0–0.25mm, found that reduction in dentine wall thickness was an important determinant of increased fracture susceptibility.[86] Therefore it is recommended that post and core diameter should be controlled to preserve root structure so that perforations are less likely to occur, and the tooth can resist root fracture. Post diameters should not exceed one third of the root diameter at any location, and post tip diameter should usually be 1 mm or less.[87]

2.7 Ferrule

According to the Glossary of Prosthodontic Terms,[88] the ferrule is "A metal band or ring used to fit the root or crown of a tooth." A modification of the definition had been suggested by Sorensen *et al* [7] to be a "360-degree metal collar of the crown surrounding the parallel walls of the dentin extending coronal to the shoulder of the preparation." The result is an increase in resistance form of the crown from the dentinal tooth structure. The ferrule effect has been extensively studied and still remains controversial from many perspectives.[2]

There are several advantages of this 'ferrule': It provides a "hugging" action; prevents the shattering of the root; reduces the wedging effect of a tapered post and, resists functional lever forces and the lateral forces exerted during dowel insertion.[32] It adds some retention, but primarily provides resistance form [7, 89-91] and enhances longevity.[92]

The ferrule height required to provide the protective effect has been frequently investigated. [7, 48, 93] When crowned bovine teeth were subjected to cyclic loading until the crown or post was dislodged or the post or root fractured, the resistance increased significantly with an increasing ferrule height.[8] Other studies[10, 22, 94] found that different ferrule heights did not improve the fracture resistance or change the failure pattern of the tested specimens.

A ferrule with 1 mm of vertical height has been shown to double the resistance to fracture compared with teeth restored with no ferrule.[7, 95] On the other hand, other studies reported no statistically significant difference in failure loads between teeth with a 1-mm ferrule and those with no remaining coronal tooth structure.[96, 97] In another study,[98] teeth with a 0.5-mm and 1-mm ferrule failed at a significantly lower number of load cycles than the 1.5-mm and 2-mm ferrule groups. Some studies have shown that a ferrule with 1.5 to 2 mm of vertical tooth structure provides the maximum beneficial effects in reducing the occurrence of subsequent root fractures.[91, 98] An increase in the height of the residual dentine generally provided greater fracture resistance.[99]

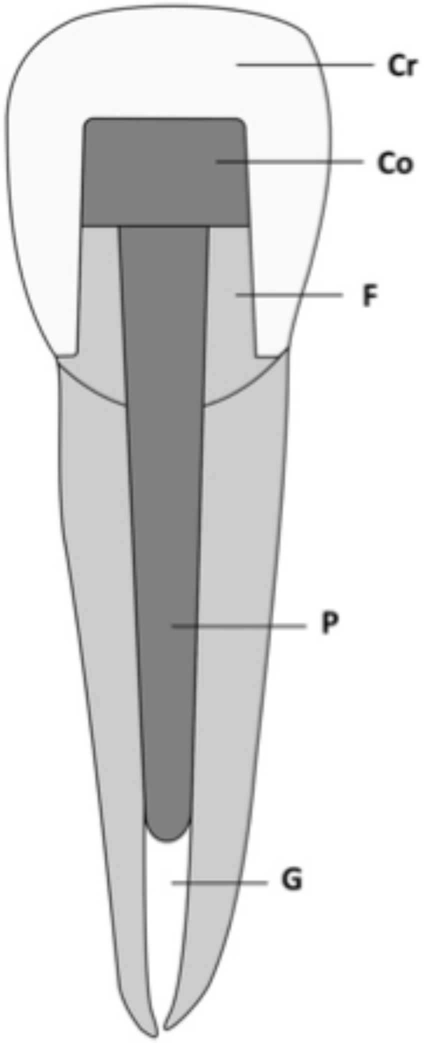


Figure 4: A schematic drawing of endodontically-treated tooth restored witb post and core system and a crown. Co=core, Cr=crown, F=ferrule, G=Gutta percha, P=Post. (Drawing taken from Juloski *et al* [2]

Since the clinical situation does not always allow preparation of the circumferential ferrule of uniform height, the effect of an incomplete ferrule on tooth resistance has also been investigated.[26, 100]

The *in-vitro* root fracture resistance of 50 endodontically-treated maxillary anterior teeth restored with fiber-reinforced posts and metal crowns and subjected to palatal loading was directly related to the circumferential extent and the sites of the 2.0 mm high ferrule preparations in coronal dentine. The highest fracture resistance loadings were found for complete circumferential and palatal sited ferrule preparations and the lowest for no preparations.[101]

A study by Naumann *et al* in 2006 [26] compared the fracture resistance of endodontically-treated maxillary central incisors with incomplete crown ferrules after chewing simulation. A ferrule of non-uniform height, varying between 0.5mm proximally and 2.0 mm buccally and lingually, was less effective in preventing failure under static loading than a uniform 2-mm ferrule. They concluded that the absence of portions of a crown ferrule (missing facial or palatal aspects, proximal interrupted) is associated with greater change of failure load and that strength values might be reduced to below a clinically acceptable load bearing. Another study[102] on the effect of different ferrule designs on the fracture resistance of upper incisor teeth restored with bonded post and cores, found that a facial ferrule increased the fracture resistance.

Not all investigations provide supporting evidence, with some studies reporting no difference in resistance between teeth with a uniform ferrule and a ferrule that incorporated only the buccal and/or lingual wall.[9, 10, 94] Nonetheless, teeth with a non-uniform ferrule length were still be more fracture resistant than those without a ferrule.[94, 100] Interestingly the height of the ferrule appears to be less significant in endodontically-treated teeth restored with fiber-reinforced (FRC) posts and resin composite cores because these materials have a similar elastic modulus to dentine.[9, 103] On the other hand the problem with minimum ferrule in FRC posts and composite core restored teeth is the micromovement in some FRC posts, leading to open margins at the core-dentine interface.[104] A study by al-Hazaimeh and Gutteridge[10] reported no difference in fracture resistance with or without a 2-mm ferrule using prefabricated posts and resin cement. However, the fracture patterns were more favorable when a ferrule was present. The majority of the fractures in the teeth without a ferrule were unrestorable.

When there is insufficient ferrule effect, the clinician may consider either orthodontic extrusion or surgical crown lengthening.[105] Both methods results in reduction in root length, leading to a compromised crown-to-root ratio; discomfort to the patient; increased cost and longer treatment time. Moreover, they may produce adverse aesthetic results and weaken the tooth, because of a more apical finish line, which results in a decrease in the cross-section of the preparation.[106, 107] Therefore the biological cost of getting this support in teeth with no coronal dentin is the additional loss of tooth tissue and, although a ferrule is desirable, it is doubtful whether it should be provided at the expense of the remaining coronal or root structure.[91, 108] However, it is important to bear in mind that a ferrule is just one part of the restored endodontically-treated tooth. The clinical performance of the entire complex is affected by other factors including the post and core material; the luting agent; the overlying crown; and functional occlusal loads.[109]

Interestingly in most of laboratory and FEA studies, single-rooted teeth have been investigated and, as a result, the influence of the ferrule effect on multirooted teeth remains largely unexplored. Also, current literature lacks information on optimal ferrule thickness. It is affected by the tooth structure remaining after endodontic treatment and the amount of dentine removed during crown preparation, which depends on the design of the finish line and crown type. However, this topic has not been widely investigated to date.[2]

2.8 Measuring the remaining tooth structure

Bandlish *et al* [110] developed a method for measuring remaining coronal dentine in root-treated teeth using a series of interlocking special trays and impressions to produce a cast of the amount of remaining dentine coronal to the finish line after crown preparation. This cast was scanned using a laser profilometer and the volume of remaining dentine was calculated. A tooth restorability index (TRI)[111] was developed to assess the strategic value of the remaining dentine. The TRI allowed scores of 0–3 in each sextant with a maximum score of 18 per tooth. To some extent the volume calculation of residual coronal tooth structure done in these studies[110, 112] does not give an indication of the strategic value of the remaining tooth structure. The volume might be distributed in areas that are not important to resist occlusal forces, or in areas with undermined walls and thin walls at the finish line area, so compromising the effectiveness in resisting forces. This was shown in their results where there was a good correlation between the volume of remaining coronal tooth structure and the TRI but this correlation was weaker when the height-width ratio of tooth structure was unfavorable.[112]

In another study Naumann *et al* [5] classified defect size using three parameters:

1. Remaining tooth substance in the vertical dimension. This was into 4 levels;
   - Level A: original crown height intact,
   - Level B: more than half of original crown height present,
   - Level C: less than half of original crown height present,
   - Level D: complete loss of original crown height.
2. Remaining tooth substance in the horizontal dimension as assessed from the

occlusal view. Using a periodontal probe (mm; bucco- lingual and mesio-distal)

3. Size of the access hole orifice (mm).

On the basis of inter-and intra observer reliability they concluded that their developed classification could be applied as an appropriate and reproducible method to define defect extension in endodontically-treated teeth.

Most recently Davis *et al*[113] developed a method for measuring local dentine thickness following tooth preparation for metal ceramic crowns using x-ray microtomography scans of extracted upper central incisors before and after crown preparation. They generated three- dimensional color-coded maps of dentine thickness. This method can be useful in dental research for quantifying and visualising the remaining dentine thickness and allowing preparation techniques and instrumentation to be evaluated *in vitro*, leading to prospective improvements in clinical procedures.

2.8 Restoration of endodontically-treated teeth

A successful clinical outcome for endodontically-treated teeth depends on a successful root canal treatment and subsequent restorative treatment.[114] Therefore, research has focused on finding the optimal post and core system,[115] luting agent[116, 117] and crown type.[118, 119] Despite the wide ranging efforts used to reinforce endodontically-treated teeth, biomechanical failures still constitute a significant issue.[71, 120]

Ray and Trope[121] evaluated the relationship between the quality of the coronal restoration and root canal filling by examining radiographs of endodontically-treated teeth. They observed that a combination of good restorations and good endodontic treatments resulted in absence of periapical inflammation in 91.4% of the teeth, whereas poor restorations and poor endodontic treatments resulted in periradicular inflammation in 82.9% of the teeth examined.

Every additional restorative step towards a final crown-restored endodontically-treated tooth was found to significantly increase its load resisting capability.[122] Many studies have demonstrated effective coronal reinforcement of tooth structure with bonded restorations.[33, 123] Composite resins and glass ionomer cements reinforce remaining tooth structure by bonding to dentine and enamel.[124] Accordingly they could enhance their resistance to fracture.

Some believe that there is no increase in tooth resistance to occlusal forces with the use of posts and that, the primary purpose of a post is to retain a core in a tooth with extensive loss of coronal tooth structure.[125, 126] However, preparation of a post space adds a certain degree of risk to a restorative procedure and can result in substantial tooth weakening.[127, 128] For the inserted post to perform its function, several variables must be considered including: post length; post diameter; geometric design; surface configuration[129] and composition in order to ensure adequate distribution of the functional stresses and to prevent root fracture.[130] Post and core selection should be based on the preservation of maximal sound tooth structure and the apical seal.[39]

Procedural errors may occur during post-space preparation. Although they are not very common, these accidents can include perforation either in the apical portion of the root or along the lateral wall of the midroot, a “strip perforation.” The placement of posts also may increase the chances of root fracture[129] and treatment failure,[131] especially with over preparation of the post channel or using posts of large diameter.[132] For these reasons, when possible, the use of posts should be restricted to provide core retention if required.[61]

2.8.1 Different core materials used

In recent years, the choice of core materials for restoration of root-filled teeth has changed from the exclusive usage of very rigid materials to materials with mechanical characteristics comparable to dentine.[133] Kovarik *et al* [134] investigated the fatigue life of three core materials (amalgam, composite resin, and glass ionomer) and prefabricated stainless steel posts. There was significant difference in the survival of the post-core-crown restorations depending on the core buildup material used. Amalgam cores had the lowest failure rate, followed by composite resin cores. All teeth restored with glass-ionomer core buildup failed. In other studies[135-138] all the groups restored with adhesive techniques, presented significantly higher fracture resistance values than the group restored with the non-adhesive technique

Amalgam has been used as a buildup material for many years, with well-recognized strengths and limitations. It has good physical and mechanical properties [139] and works well in high-stress areas.[134] In some situations, there is a need for the addition of pins or other methods to increase retention and resistance of the restoration. Placement can be difficult when there is minimal coronal tooth structure, and the crown preparation must be delayed till the material sets. Amalgam can compromise aesthetics especially with ceramic crowns and sometimes makes the gingiva appear dark. Due to the potential concern about mercury and the possible risk of tattooing the cervical gingiva with amalgam particles during the crown preparation, it is no longer widely used as a buildup material.[140]

Glass-ionomers, including the resin-modified materials, lack adequate strength as a core material[141, 142] and should not be used in teeth with extensive loss of tooth structure. When there is minimal loss of tooth structure and a post is not needed, glass-ionomer materials work well to block-out undercuts, or in small restorations.[61]

Nowadays, resin composite has become more popular as a core material as it has some of the characteristics of an ideal buildup material.[61] It has a long history of use as a core material due to its ease of manipulation and high tensile strength. The material is available in light-cured, auto-polymerized, and dual-cured formulations that facilitate preparing the tooth for a crown immediately after polymerization. It comes in different tooth color shades and can be used under translucent restorations without affecting the aesthetic result.[143, 144] The main advantage of composite is its ability to bond to tooth structure as well as some of the current posts. It also can serve as a substrate, to which a ceramic crown can be bonded.[61, 145]

On the negative side, resin composites shrink during polymerization, causing gap formation in the areas in which adhesion is weakest. It absorbs water after polymerization,[146] and undergoes plastic deformation under repeated loads.[134, 139] Adhesion to dentine on the pulpal floor is generally not as strong or reliable as to coronal dentine.[147] Tooth isolation is essential requirement for resin core placement. If the dentine surface is contaminated with blood or saliva during bonding procedures, the adhesion is greatly reduced.[61]

When adequate sound dentine- supported enamel is present, intracoronal bonded resin composite restorations might demonstrate a better clinical performance in preventing tooth fractures in endodontically-treated teeth than similar amalgam restorations. This was supported by Hansen *et al* [72] who found fewer short-term cuspal fractures in endodontically-treated premolar teeth with MOD resin composite restorations than with MOD amalgam restorations. Pilo *et al*.[148] showed that composite cores have a fracture resistance comparable to amalgam and cast post and cores, with more favorable fracture patterns when they fail.

An *in vitro* study[149] of 12 extracted human maxillary premolars with large MOD and access cavity preparations found that improvement in the cuspal stiffness is achieved by a resin composite base compared to a conventional glass ionomer cement base. However, after placement of the final resin composite and ceramic restorations there was no longer a significant difference between teeth with different base materials[149]. This is supported by a more recent study where the fracture resistance of root canal dentine was improved by composite resin compared with glass ionomer cement.[33]

2.8.2 The use of full crowns

There is a strong consensus from the available data, that cuspal coverage restorations ought to be offered for posterior root-canal treated teeth[61,74] especially when the cusps have been weakened. Cuspal coverage with bonded resin composite, amalgam, cast metal alloy, or high-strength ceramic materials is essential to prevent tooth fractures. An *in vitro* study by Panitvisai and Messer[79] showed that access preparations result in greater cuspal flexure, increasing the probability of cuspal fracture.

A systematic review[150] of single restorations in endodontically-treated teeth reported that the estimated survivals were 81% for crowned teeth and 63% for direct restorations (resin composites, amalgams, cements) at 10 years.

Aquilino and Caplan[151] found a strong association between crown placement and the survival of endodontically-treated teeth. They reported that root-filled teeth without crowns were lost at a six times greater rate than teeth with crowns. They suggested cusp coverage to restore the fracture resistance because they protect cusps from the outward deflection. Smales and Hawthorne[152], reported lower 15-year survival rates for complex cusp-covering amalgam restorations (48%) compared to crowns (89%).

One of the most often cited series of studies on endodontically-treated teeth by Sorensen and Martinoff[124, 131] evaluated the effect of tooth location, coronal coverage, and intracoronal reinforcement on the success of 1273 root-canal treated teeth over an observation period of 1 to 25 years. The results indicated that crown placement had no significant effect on the success of anterior teeth but significantly improved the clinical success rates of posterior teeth. This was in agreement with another independent, retrospective study of 608 endodontically-treated teeth that evaluated the factors affecting their survival during a 10-year period. [92] Again cuspal coverage was one of the significant factors that predicted long-term success. These results support the concept that crowns generally should be offered for endodontically-treated posterior teeth and on anterior teeth with substantial loss of tooth structure.[126]

Scurria *et al*. [153], in reviewing the insurance claim found that despite strong evidence of the benefits of cuspal coverage it is not yet generally provided for endodontically-treated posterior teeth. They found that 37 percent of premolars and 40 percent of molars did not receive extracoronal or cuspal coverage restorations. Eckerbom and Magnusson[154] also reported similar findings from a survey of restorative dentists.

On the other hand indirect full coverage restorations have some disadvantages including: the high cost of the laboratory procedure; the significant amount of sound tooth structure that has to be sacrificed; and the considerable treatment time spent on such complex restorations[21, 155] Partial coverage restorations conserve more tooth structure than a complete coverage restoration. Only few studies have been published addressing the advantages and disadvantages of partial coverage restorations for teeth. Two studies compared the differences in the amount of tooth structure removal using various preparation designs on anterior Typodont resin teeth[156] and extracted human teeth. [157]

Edelhoff and Sorensen[156] carried out an *in vitro* study to determine and compare the amount of tooth structure removed for laminate veneer and resin-bonded prostheses in comparison with conventional complete coverage restorations. They found that the veneers and resin-bonded prostheses preparations required 25% to 50% less reduction than that required by complete coverage restorations.

In another study by Murphy *et al* [112] the volume of remaining coronal tooth structure after complete coverage preparation varied from 112.23 mm^3 to 296.60 mm^3 compared with 157.54 mm^3 to 386.34 mm^3 for the same teeth prepared for partial coverage restorations. The percentage loss of volume of coronal tooth structure that occurred by providing a complete instead of a partial coverage restoration varied from 3-29% to 45-23%.

Currently, evidence for the relative effectiveness of conventional fillings over crowns for the restoration of root canal treated-teeth, is inconclusive. Until more clinical data available clinicians will base their decisions on their own clinical experience, taking into consideration the individual circumstances and preferences of their patients.[158]

AIM OF THE STUDY

The aims of this study are to:

1. Measure the cross-sectional area of the remaining coronal tooth structure of endodontically-treated maxillary premolar teeth at the level of the finish line after the removal of different patterns of remaining coronal structure simulating different clinical situations.
2. Assess the resistance to fracture of these teeth after restoration under simulated occlusal load
3. Assess the relationship between the cross-sectional area the location of remaining coronal tooth structure and the fracture resistance.

MATERIALS AND METHODS

The Human Research Ethics Committee, University of Adelaide, granted ethical approval for this study. (Approval Number H-110-2010)

4.1 Collection of teeth

Fifty- five freshly extracted, intact, restoration free, disease free, mature, single or double rooted upper premolars were collected from the Oral and Maxillofacial Surgery Department in the Adelaide Dental Hospital, mainly from people undergoing dental extractions as part of orthodontic, orthognathic, prosthodontic or periodontal treatment. (Figures 5 and 6)

Figure 5: Proximal view of upper premolar

Figure 6: Occlusal view of upper premolar tooth

4.2 Specimen preparation

Initial preparation of the teeth involved the removal of any superficial staining, calculus, and adherent soft tissue using an ultrasonic scaler (EMS, Switzerland) and subsequent polishing with a rotary polishing brush (Guangzhou Bytech, China) and pumice/water mixture (Zircate, Dentsply). The teeth were examined with optical loupes at x2.5 magnification to ensure they were free from caries, restorations, crazing, and fractures. The buccolingual and mesiodistal dimensions were measured at the cementoenamel junction using a thickness gauge (Iwansen, China), The length of each tooth was also measured to ensure that teeth of similar sizes were included in each of the study groups. Minimizing specimen variation allowed for meaningful comparisons to be made between different groups. Teeth were kept hydrated at room temperature in distilled water at all times during the study other than during the operative procedures and testing.

4.3 Root canal preparation:

A conservative oval access cavity was prepared in the centre of the occlusal surface between the cusps using a high speed hand piece with carbide round bur (Komet, Halas, USA) until the canal orifices were identified. (Figure 7)

A hand file (Maillefer, Dentsply, Germany) size 10K was inserted till the tip of the file was visible at the apical foramen, and this length was measured. A set length of 0.5 mm was deducted from this measurement to reach the working length. The teeth were prepared with hand files (Maillefer, Dentsply, Germany) using the step back technique to at least #25 at the working length then flared coronally by three sizes up the master apical file. Milton solution was used to irrigate the canals between each file change and paper points (Zipper, Dentsply, Germany) were used for drying. The canals were then obturated with gutta percha master cones (Zipper, Dentsply, Germany), fine accessory cones and root canal sealer (AH26, Dentsply, Germany) using the lateral condensation technique. After obturation the gutta percha was reduced to the canal orifices using a heated plugger. The access cavities were then wiped with alcohol to remove excess sealer.

Figure 7: Occlusal view of upper premolar tooth with endodontic access cavity and root canal obturation

4.4 Full crown preparation

Two addition silicone (Honigum, DMG, Germany) reduction guides were fabricated for each tooth. These were sectioned in a mesiodistal and bucco-lingual plane and used as reference guides to standardize tooth reduction by measuring the distance between the tooth surface and the fitting surface of the reduction guide.

All teeth were prepared by the same operator using 2.5x optical loupes and under constant water-cooling. A 1mm deep chamfer finish line was made 1mm above and following the cement-enamel junction[7] using a round end diamond rotary cutting instrument (Komet, Halas, USA). (Figure 8)

Figure 8: Occlusal view of upper premolar after endodontic occlusal access cavity and crown preparation.

4.5 Sample grouping:

After crown preparation, teeth were randomly assigned to 11 groups each of 5 teeth to ensure that the distribution of root dimentions were comparable in each group. Power calculations based on the data published by Ng *et al* [101] showed that a sample size of five was adequate to demonstrate difference 150N.

Each group of teeth received different tooth preparations according to the missing wall(s) as shown in Table (1) and Figure (9). The 11 groups include all possible combinations of missing;

- Occlusal (O)
- Buccal (B)
- Palatal (P)
- Proximal (M, D, or Px when mesial and distal combinations would give a mirror image alternatives)

Table 1: Sample grouping according to the missing wall(s): O= Occlusal access, Px= Proximal, P=Palatal, B= Buccal, M= Mesial, D= Distal

	1 surface	2 surfaces			3 Surfaces				4 Surfaces		
Group	1	2	3	4	5	6	7	8	9	10	11
Missing wall	O	OPx	OP	OB	MOD	BOP	BOPx	POPx	MODP	MODB	BOPPx

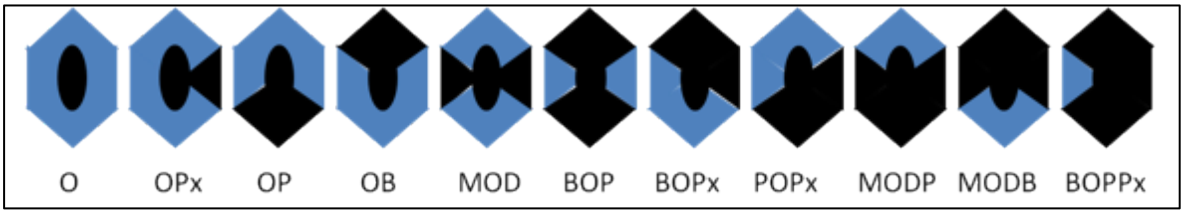


Figure 9: Sample grouping

4.6 Surface area analysis:

In order to measure the amount of coronal dentine remaining after access cavity and crown preparation, an impression of the prepared teeth was taken using small plastic trays and light and medium consistencies of addition silicone impression material (Honigum, DMG, Germany) This was poured with epoxy resin (Megapoxy, Vivacity Engineering Pty, Ltd, Australia) to construct a die for each tooth. (Figure10)

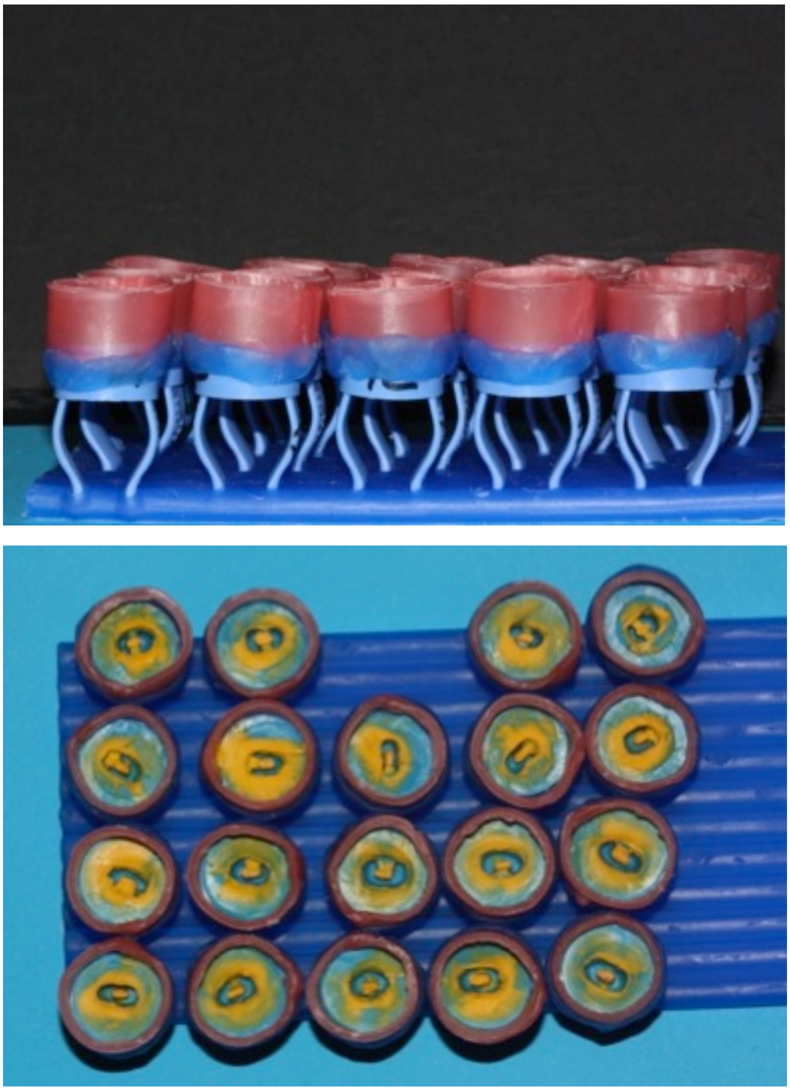
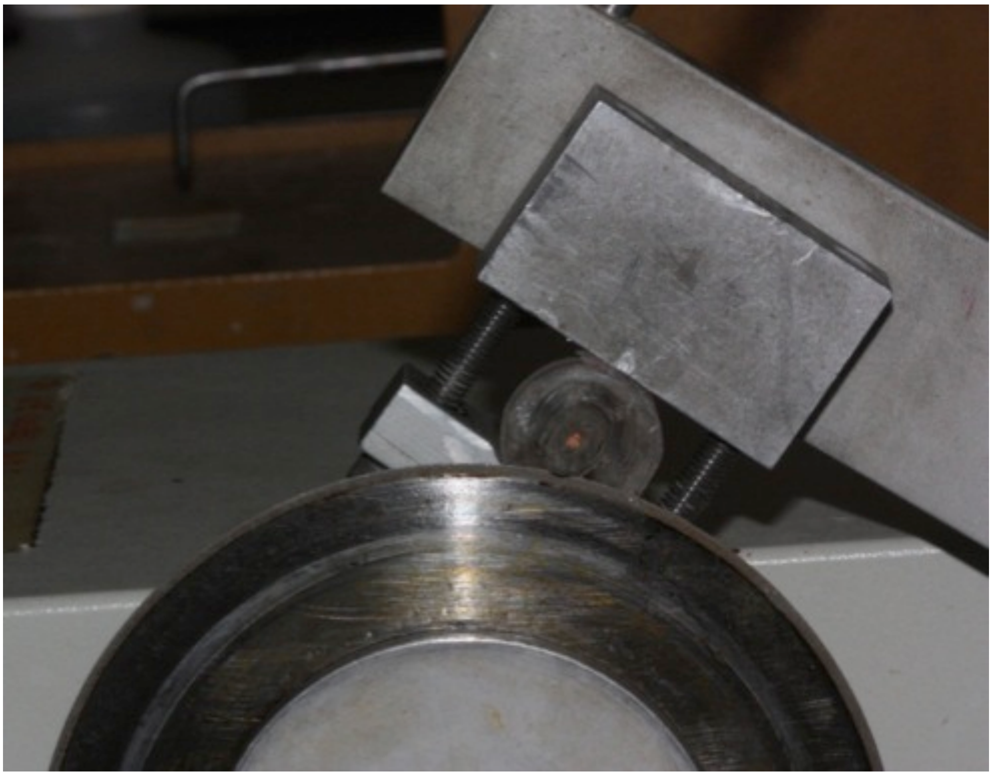


Figure 10 : Impression taken for the specimens ready to be poured to form the dies

The epoxy dies were sectioned 1mm above the most occlusal point of the finish line using an Isomet slow speed sectioning machine (Beuhler, lllinois, USA) (Figures 11and12) and photographed from an occlusal view at 90 degree to the long axis of the die using a SLR camera (Canon EOS 450) and a macro lens (Canon Macrolite 100mm).

Figure 11: Isomet slow speed sectioning machine (Beuhler, Illinois, USA)



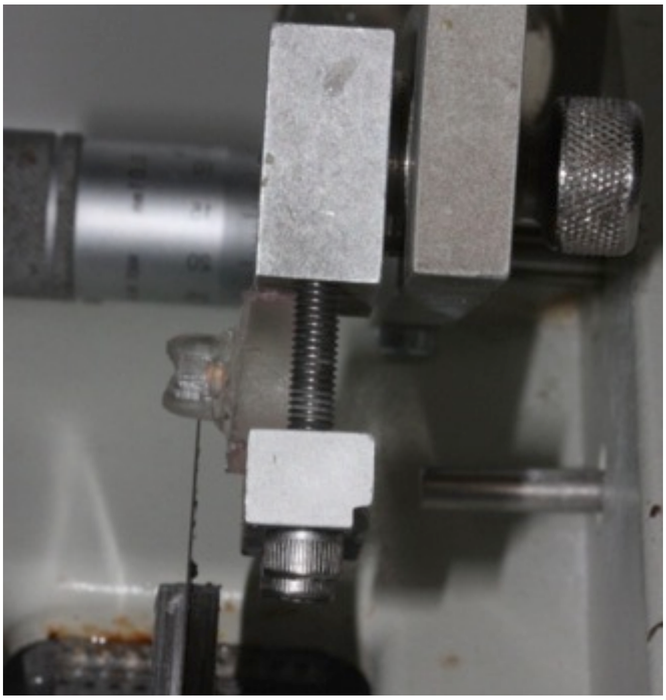


Figure 12: the epoxy die mounted in the slow speed sectioning machine.

The images were analysed using imageJ software[1] to calculate the surface area of the remaining coronal tooth structure 1 mm above the highest contour of the finish line. (Figure 13) The reproducibility and validity of the method was tested in a previous study[159], where images of arbitrary shapes of predetermined area were created. Each image was scanned four times to obtain digital images, making a total of 20 images for analysis. The surface area of the shapes was analyzed using "ImageJ" on two occasions, two weeks apart. There was no significant difference between the first and the second determination ($p>0.05$). The reproducibility of the measurement was tested as well and no significant differences were found between the two determinations as analyzed by paired t-test ($p>0.05$).[159]

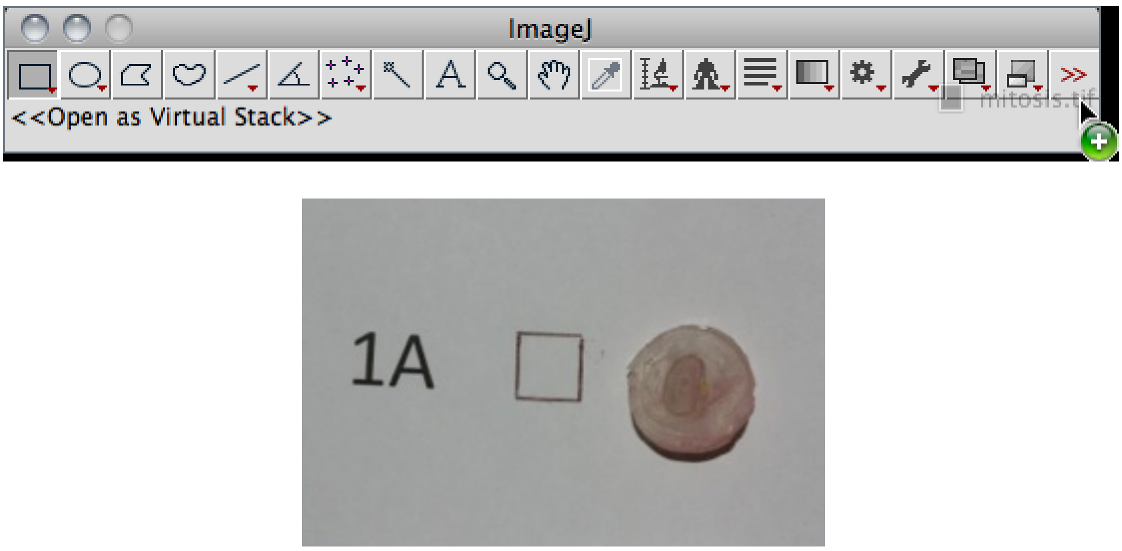


Figure 13: Measuring the surface area of the sectioned dies using imagej computer software

4.7 Core build up

The dentine was conditioned with polyacrylic acid (GC Fuji plus conditioner, GC corp., Tokyo, Japan) and a 2 mm base of glass ionomer (Fuji IX; GC corp., Tokyo, Japan) was applied. When the glass ionomer had set, each tooth was etched with 37% phosphoric acid solution (Adper™ Scotchbond™ Etchant, 3M ESPE) for 30 sec around the cavity, then washed with water for 20 sec and dried with air. Primer and bonding adhesive (Scotchbond Multi-Purpose System, 3M ESPE) were applied according to the manufacturer's instructions and light-cured for 20 sec. The composite resin (Filtek Supreme XT, 3M ESPE) was placed into the cavity incrementally with each increment light-cured for 40 sec using a visible-light curing unit (XL2500, 3M; light intensity, 580 mW/cm2).

4.8 Crown fabrication

The porcelain fused to metal crown was not used in this study to avoid the additional complications from the unexpected failure of porcelain.[32]

One laboratory technician fabricated all wax patterns for the cast metal crowns. The patterns were formed directly on the tooth specimens coated with a lubricant (Isolit, DeguDent GmbH, Germany) to facilitate pattern removal. The correct thickness of the wax pattern was verified by using a caliper (Iwansne guage). A small groove was placed across a flat facet on the mid palatal surface of the buccal cusp of each crown at 45 degrees to the long axis of the tooth to prevent the loading rod from slipping. This groove was carved into the wax patterns using the loading device for the universal testing machine, The wax patterns were invested in high expansion phosphate-bonded investment material (Speed Vest, Argibond, Germany) and cast using a Type 3 crown and bridge alloy (Argeloy Sunray, The Argen Cooperation, USA). (Figure 14)

NOTE:
This figure/table/image has been removed
to comply with copyright regulations.
It is included in the print copy of the thesis
held by the University of Adelaide Library.

Figure 14: The percentages of the main constituents of the alloy used (Argeloy Sunray, The Argen Cooperation, USA)

The teeth specimens were cleaned using a prophy cup and oil-free pumice, and rinsed with water to remove any lubricant residue. The cast crowns were cemented with resin cement (RelyX Unicem, 3M ESPE) under a static firm finger pressure. The excess cement was removed with a microbrush and the margins were light cured from all directions. (Figure 15)

Figure 15: Proximal view of the tooth after crown cementation.

4.9 Thermocycling

All specimens were subjected to thermocycling as outlined in ISO TR 11450 standard (1994).[17, 18, 21] Specimens were subjected to 500 cycles exposed to 5 °C and 55 °C each for 20 seconds each with an intermediate pause of 3 seconds transfer time between hot and cold water baths. (Figure 16)

Figure 16: Thermocycling machine

4.10 Mounting of samples

The experimental teeth were then mounted using autopolymerizing acrylic resin (ProBase Cold, Ivoclar Vivadent, Leichenstein) within a brass cylinder (2cm diameter, 2.5cm height) to a level 1 mm below the CEJ. A dental surveyor (J.M. Ney Company, Hartford, USA) was used to ensure that the teeth were mounted parallel to the long axis of the holding device.[22](Figure 17) The cylinders were placed in a water bath to disperse the heat generated during polymerization.[9, 26] (Figure 18)

Periodontal ligament (PL) simulation was not considered in the current study [17, 160] for a number of reasons including:

1. The benefits of using such materials are questionable since the elasticity is different to that of the PL.[10]
2. Difficulty in standardizing the thickness of the silicone material along the circumference of the roots.
3. Uncertainty about variation in the dimensions of the PL. along the length of the roots. There is no practical way this phenomenon can be simulated *in vitro*.
4. The effect of the P.L. to dissipate occlusal forces is mainly in dynamic loading. When the tooth is subjected to static load, the PL. will maximally deform initially after which time all the force will be transmitted to the surrounding bone which is simulated in this study be the autopolymerizing acrylic resin. [160]
5. Loosening of teeth within embedding material during testing has been reported.[10, 11] It is not certain whether the presence of PL simulating material between the root and the acrylic resin can lead to slippage of the tooth in the mounting assembly.

6. A previous study[25] showed that the presence of a periodontal simulation during testing affects mainly the mode of fracture. In this study the mode of fracture was not the main focus.

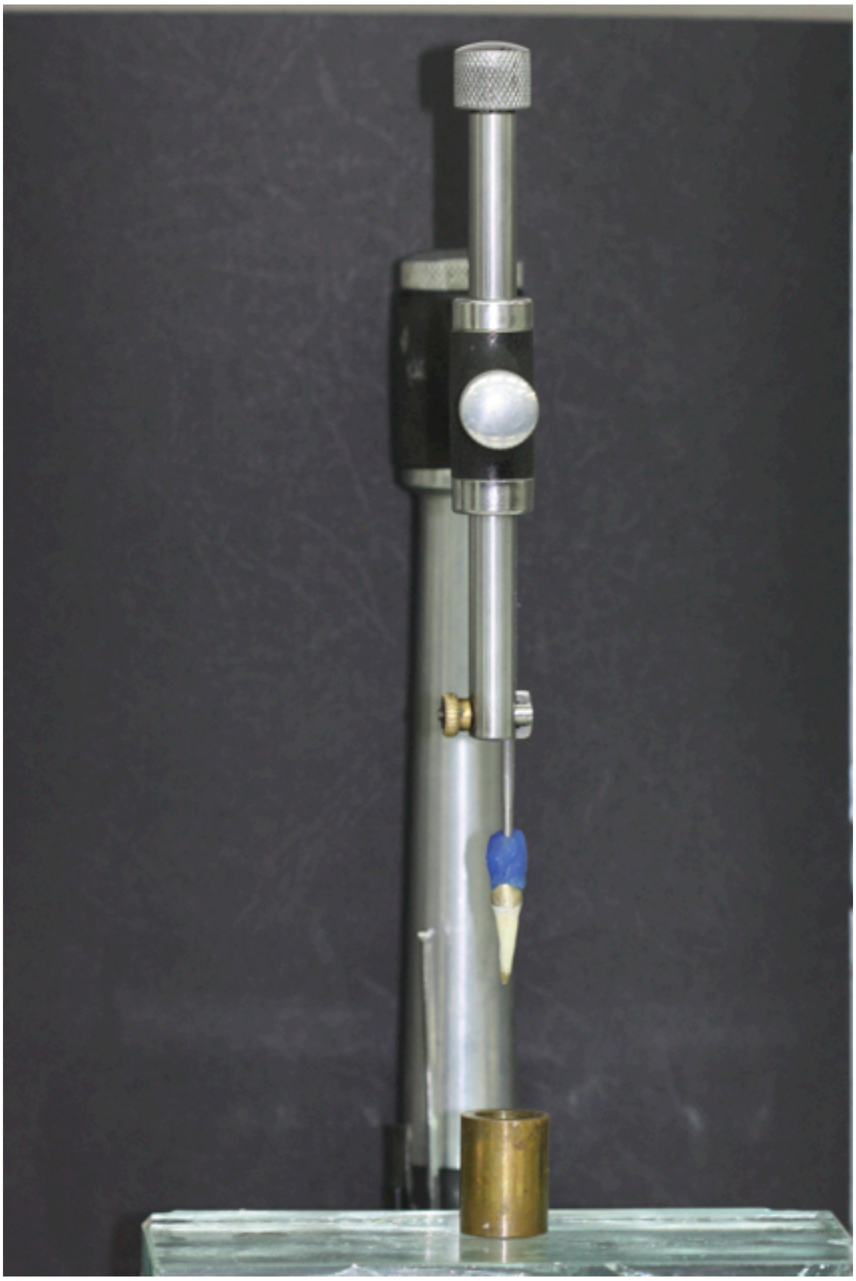


Figure 17: Mounting of the tooth in the brass ring using the surveyor

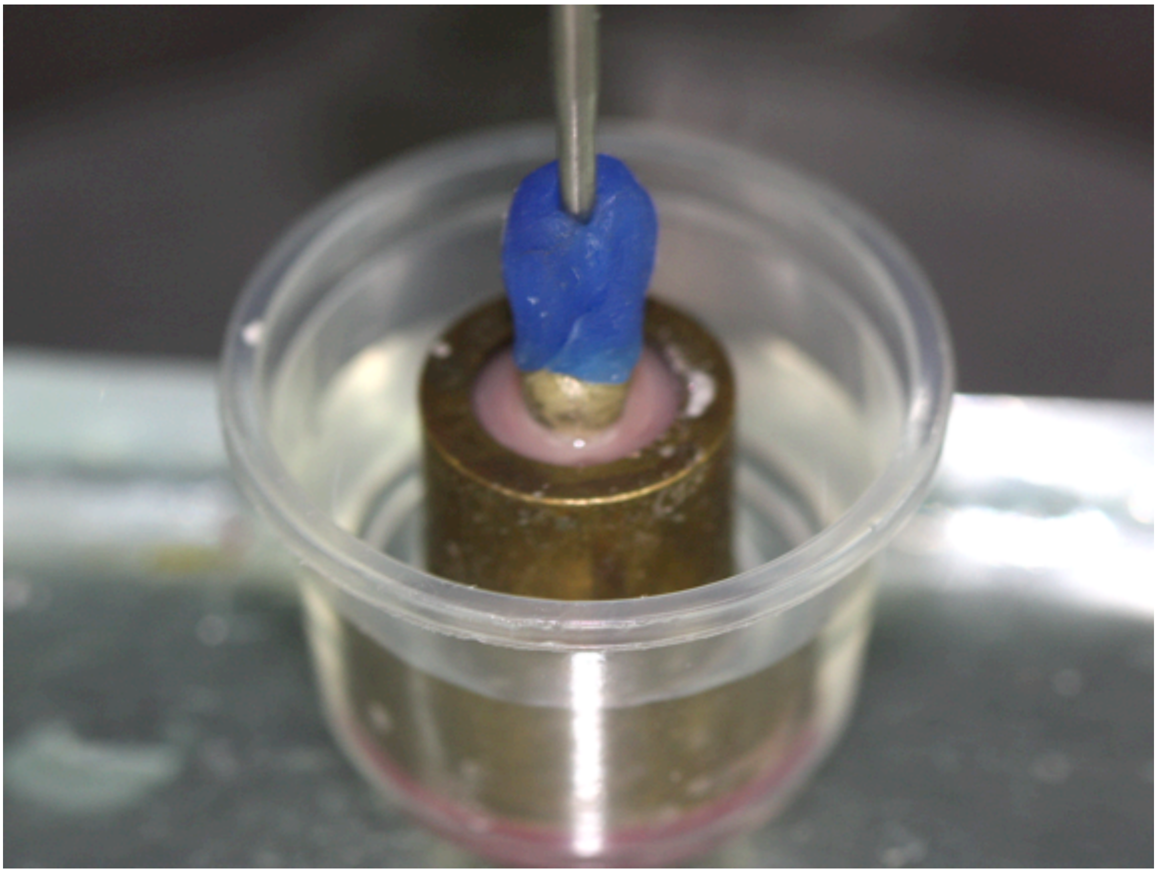


Figure 18: The brass cylinder was placed in a water bath as the acrylic resin is polymerized.

4.11 Fracture testing

The fracture testing of specimens was performed using a Hounsfield H50K Universal testing machine (Hounsfield Test Equipment Ltd., England) with a maximum load cell of 2000 Newtons and a cross head speed set at 1mm/min.[19, 38, 161] A compressive load was applied to tooth specimens through a hardened steel 3.5mm chiselled edge spike fitted into the small manufactured groove on the palatal surface of the buccal cusp of the crowns to prevent slippage (see section 4.8). The load was applied at an angle of 45 degrees to the long axis of the teeth[43, 114,161] to examine the role of the remaining tooth structure in resisting the more destructive non-axial forces. Non-functional cusps were loaded as clinical evidence suggests that these fracture more often than the functional cusps.[44]

The applied force was increased until failure occurred. A unidirectional static loading force was selected in this study as this is the most frequently used method to evaluate the strength of prepared and/or restored teeth.[20, 31-33] The 45-degree angle was achieved by securing the specimen in the testing machine using a custom made jig to support the brass cylinder. (Figure 19)

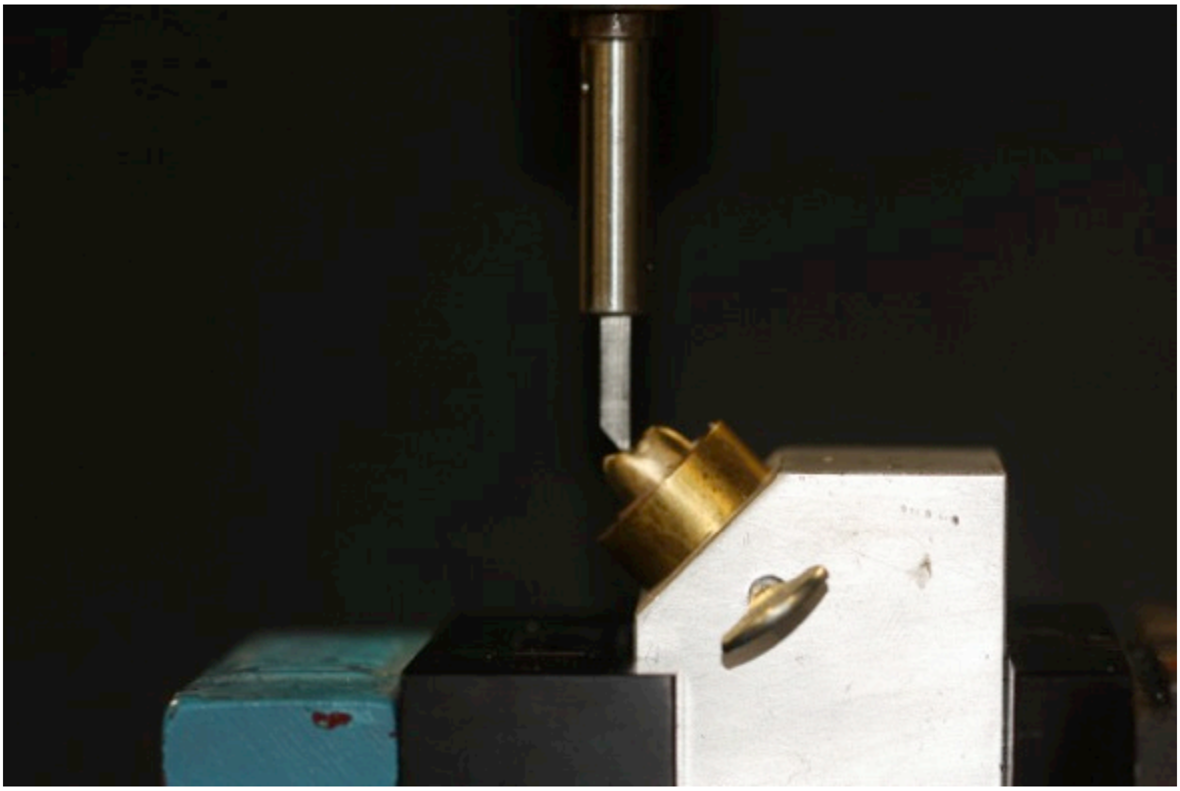


Figure 19 : Tooth mounted in the Universal testing machine with the chisel end rod applying load to the palatal incline of the buccal cusp at 45 degree angle

A force (Newtons) versus extension (mm) curve was dynamically plotted for each tooth (Figure 18) and from this, the maximum force at failure was recorded (Figure 20).

This parameter was used for group comparisons. As a matter of interest specimens were also visually examined to determine the type and location of failure.

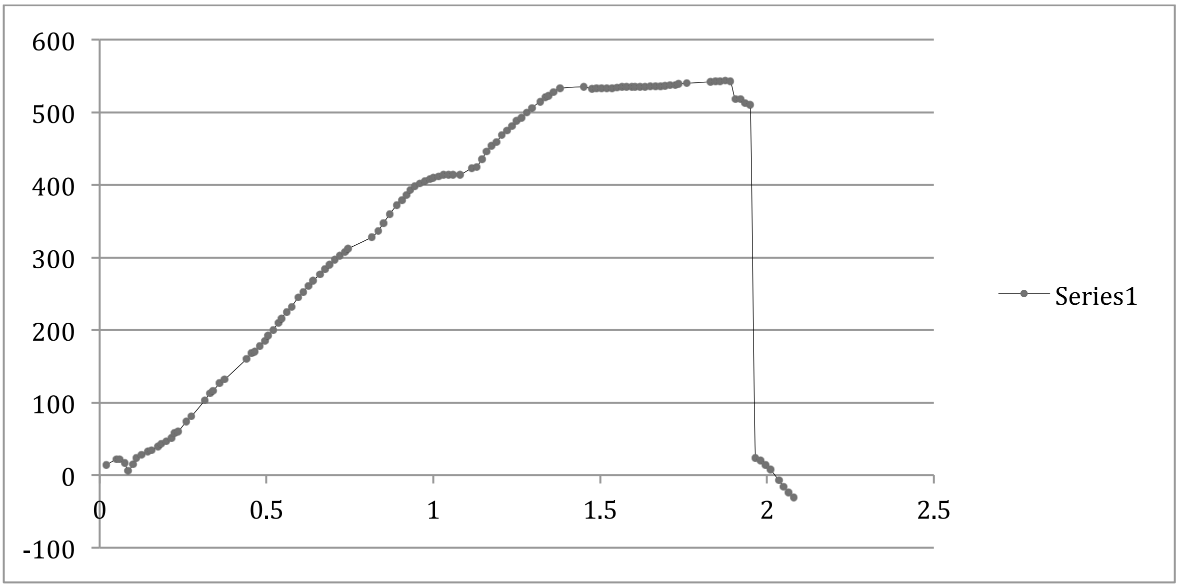


Figure 20: plot graph for a sample of group 1

4.12 Data analysis

A statistical analysis was performed to detect any significant difference in mean failure loads and mean surface areas between groups. Results were analysed using one way analysis of variance (ANOVA) and Student's t- test

RESULTS

5.1. Surface area analysis

The mean and the standard deviation of the calculated surface area for each group are shown in table 2 and figure 21. The values varied from 9.54±1.61 mm^2 to 31.38 ± 3.50 mm^2. As expected, as the number of missing walls increases the surface area of the remaining dentine decreases.

A one-way analysis of variance (ANOVA) was carried out to compare the mean values of the 11 groups. (Table 3)

Further analysis with unpaired t-test to detect the significant differences between the groups was carried out. The results are shown in Table 4.

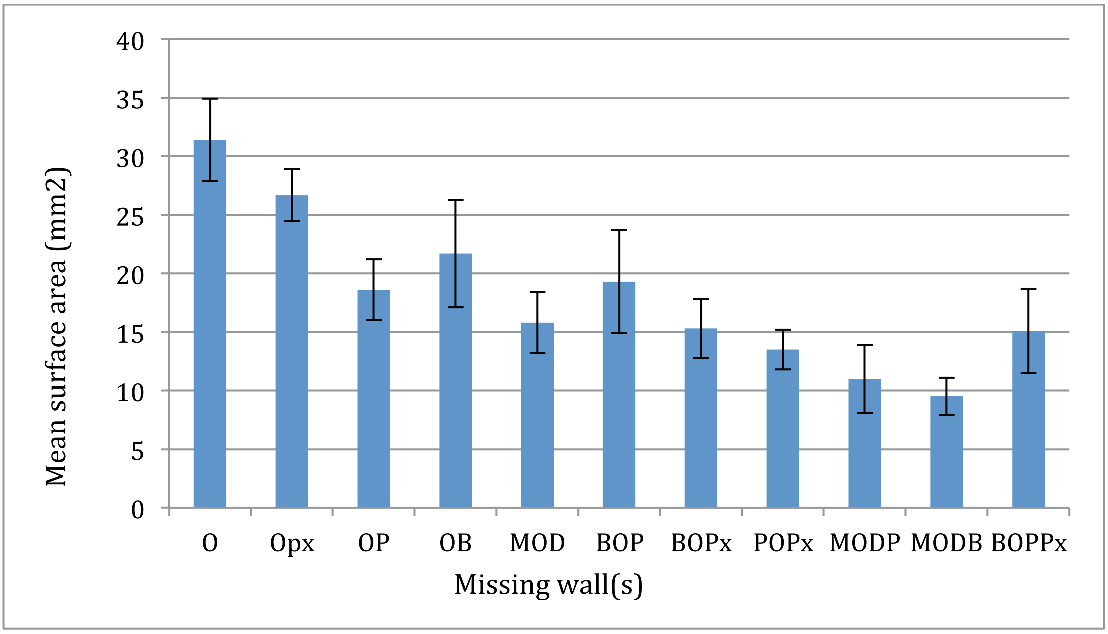


Figure 21: Bar chart for mean surface area values of all groups

Table 2 A summary of mean and standard deviation of the remaining dentine surface area of samples in mm^3

Number of missing walls	Group	Missing Surface	Number of samples	Mean (mm2)	Standard Deviation
One	1	O	5	31.3	3.50
Two	2	OPx	5	26.7	2.22
	3	OP	5	18.6	2.60
	4	OB	5	21.7	4.67
Three	5	MOD	5	15.8	2.60
	6	BOP	5	19.3	4.48
	7	BOPx	5	15.3	2.55
	8	POPx	5	13.5	1.73
Four	9	MODP	5	11.0	2.94
	10	MODB	5	9.5	1.61
	11	BOPPx	5	15.1	3.67

Table 3: Results for ANOVA statistical test for the surface area

Source of Variation	Sum of Squares	d.f.	Mean Squares	F
between	2159.	10	215.9	22.16
error	428.7	44	9.744	
total	2588.	54		

The probability of this result, assuming the null hypothesis, is 0.000

Table 4: Probability values for pair-wise comparisons of means of the remaining tooth surface area

	OPx	OP	OB	MOD	BOP	BOPx	POPx	MODP	MODB	BOPPx
Occlusal	0.0367	0.0003	0.0059	0.0001	0.0014	0.0001	0.0001	0.0001	0.0001	0.0001
OPx		0.0007	0.0609	0.0001	0.0097	0.0001	0.0001	0.0001	0.0001	0.0003
OP			0.2260	0.1191	0.7866	0.0715	0.0058	0.0024	0.0002	0.1108
OB				0.0355	0.4127	0.0249	0.0054	0.0023	0.0005	0.0342
MOD					0.1632	0.7736	0.1349	0.0264	0.0018	0.7372
BOP						0.1159	0.0247	0.0081	0.0016	0.1371
BOPx							0.2129	0.0380	0.0024	0.9173
POPx								0.1461	0.0053	0.3895
MODP									0.3289	0.0864
MODB										0.0133

(yellow)	Significant difference (P<0.05)
(green)	No significant difference (P>0.05)

5.2. Fracture strength

A total of 52 load values were available for statistical analysis. Two specimens failed at loads more than two standard deviations below the mean for their group and were excluded. One was from group 1 (occlusal) and the other from group 9 (MODP) with values 544 and 262 N respectively. A third specimen from group 4 (buccal) was fractured during adjustment of the load in the testing machine before application of significant load and being recorded by the computer, so no data was available for this specimen.

Mean failure loads and the standard deviations of each group are presented in Table 5 and Figure 22. A one way Analysis of Variance (ANOVA) was carried out to compare the means of the 11 groups. (Table 6)

Further analysis with unpaired t-test indicated that Group 1 had the highest fracture resistance, which was significantly different from all other groups except group 2 and 4. Among the groups with missing two surfaces, Group 3 has a significantly lower fracture resistance than group 1, 2 and 4. Comparing groups with 3 surfaces missing with each other, Group 5, 6 and 7 were not significantly different from each other but showed significantly higher fracture resistance than group 8. In the groups with missing 4 surfaces; the fracture resistance in group 9 was significantly lower than in groups 10 and 11. (Table 7)

Table 5 A summary of mean and standard deviation of the failure loads of samples in Newton.

Number of missing walls	Group	Missing walls	Number of samples	Mean	Standard Deviation
One	1	O	4	1380.5	393.93
Two	2	OPx	5	1142.8	307.96
	3	OP	5	500.4	90.21
	4	OB	4	1043.7	247.52
Three	5	MOD	5	800.8	208.82
	6	BOP	5	631.8	124.73
	7	BOPx	5	748.4	249.49
	8	POPx	5	398.4	149.59
Four	9	MODP	4	344.7	91.25
	10	MODB	5	682.8	172.29
	11	BOPPx	5	540	121.33

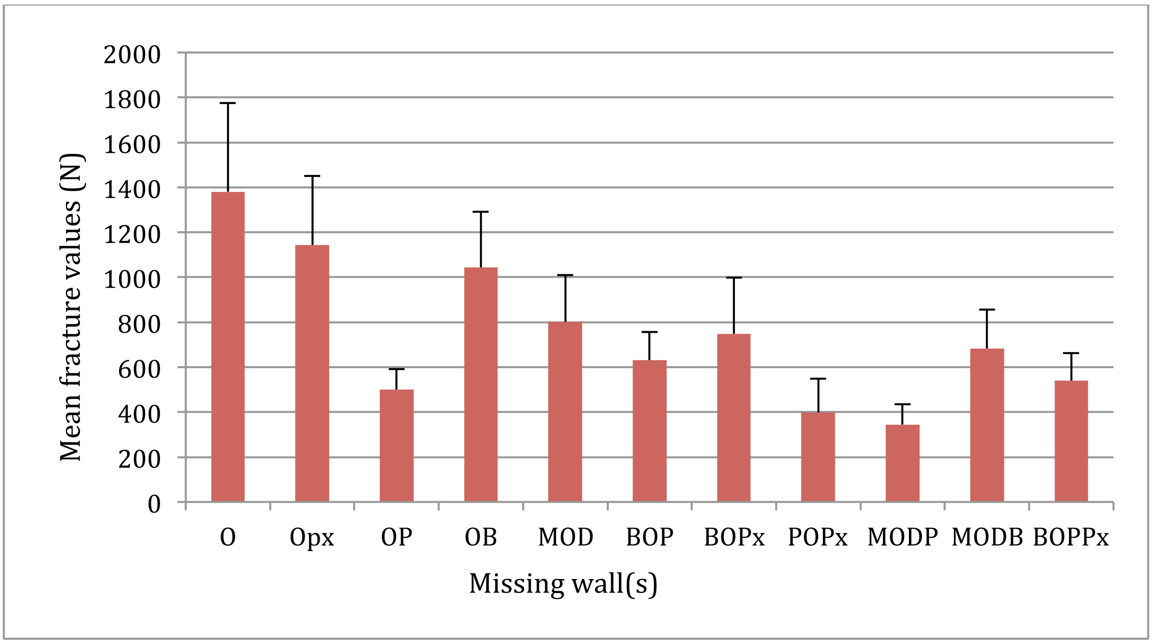


Figure 22: Bar chart of the mean fracture values for all groups

Table 6: Results of the ANOVA statistical test for the fracture resistance values

Source of Variation	Sum of Squares	d.f.	Mean Squares	F
between	4.6102E+06	10	4.6102E+05	10.28
error	1.8390E+06	41	4.4855E+04	
total	6.4492E+06	51		

The probability of this result, assuming the null hypothesis, is 0.000

Table 7: Probability values for pair-wise comparison of means of the fracture strength

	OPx	OP	OB	MOD	BOP	BOPx	POPx	MODP	MODB	BOPPx
Occlusal	0.339	0.0017	0.196	0.0240	0.0047	0.0212	0.0012	0.0021	0.0086	0.0025
OPx		0.0020	0.6179	0.0739	0.0088	0.0567	0.0013	0.0017	0.0194	0.0036
OP			0.0024	0.0183	0.0936	0.0700	0.2280	0.0376	0.0692	0.5743
OB				0.0912	0.0026	0.076	0.0003	0.0002	0.0128	0.0008
MOD					0.1573	0.7293	0.0079	0.0050	0.3580	0.0422
BOP						0.3745	0.0276	0.0065	0.6037	0.274
BOPx							0.0272	0.0188	0.6415	0.1315
POPx								0.5516	0.0237	0.1388
MODP									0.0098	0.0317
MODB										0.1680

(yellow)	Significant difference (P<0.05)
(green)	No significant difference (P>0.05)

5.3. Mode of failure

The mode of failure in most of the specimens was an oblique fracture extending from the palatal surface of the tooth at or above the CEJ, down to the buccal surface of the root. (Figure 23) A total of 12 specimens showed a similar oblique fracture pattern but at a lower level below the CEJ in the root. Two specimens in Group 1 (occlusal) showed a different failure mode represented as cement failure and dislodgment of the crown with the development of a crack in the buccal wall of the tooth above the crown margins. (Table 8)

Table 8: Mode of failure of samples in different groups

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9	Group 10	Group 11
Oblique at CEJ		5	5	4	3	5	1	4	5	4	4
Oblique below CEJ	2			1	2		4	1		1	1
Crown dislodg-ement	2										

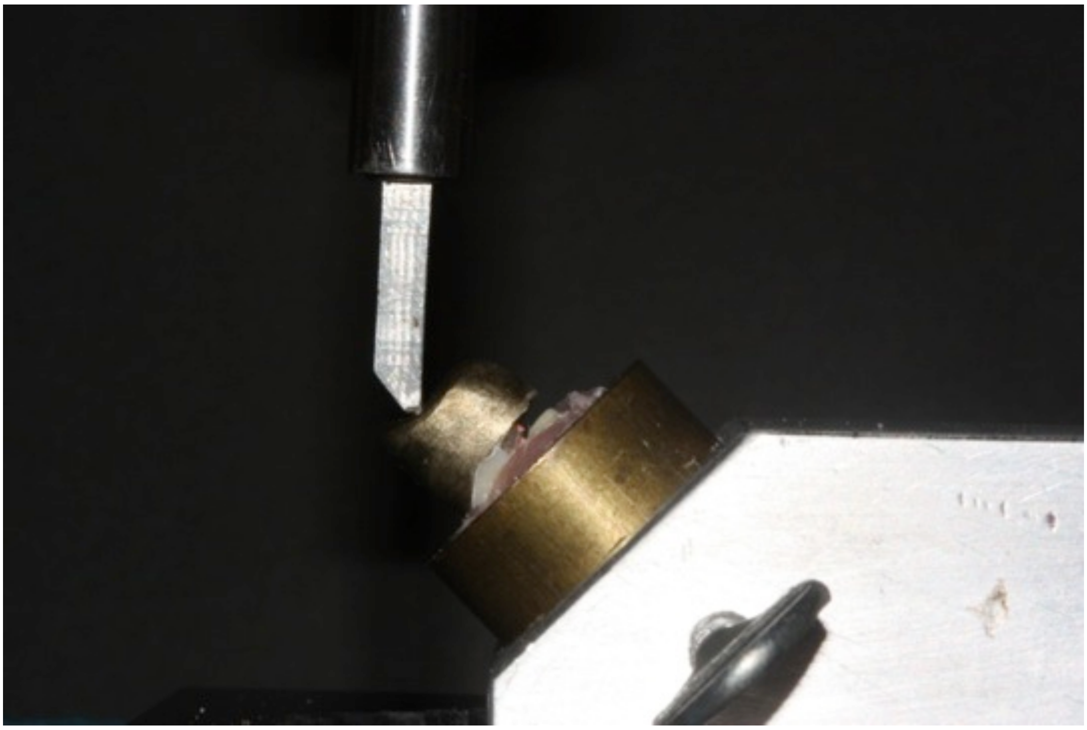


Figure 23: An example of the mode of fracture of sample during testing

5.4. Relation between the dentine surface area and the fracture strength

Figure 24 shows a scatter-plot that demonstrates the relationship between the remaining dentine surface area values in mm^2 (x-axis) and the fracture strength in Newtons (y-axis). The coefficient of variation between the two variables was R^2=0.52 indicated that the surface area of the remaining dentine is strongly related to the fracture strength, explaining more than 50% of the total variation in fracture strength.

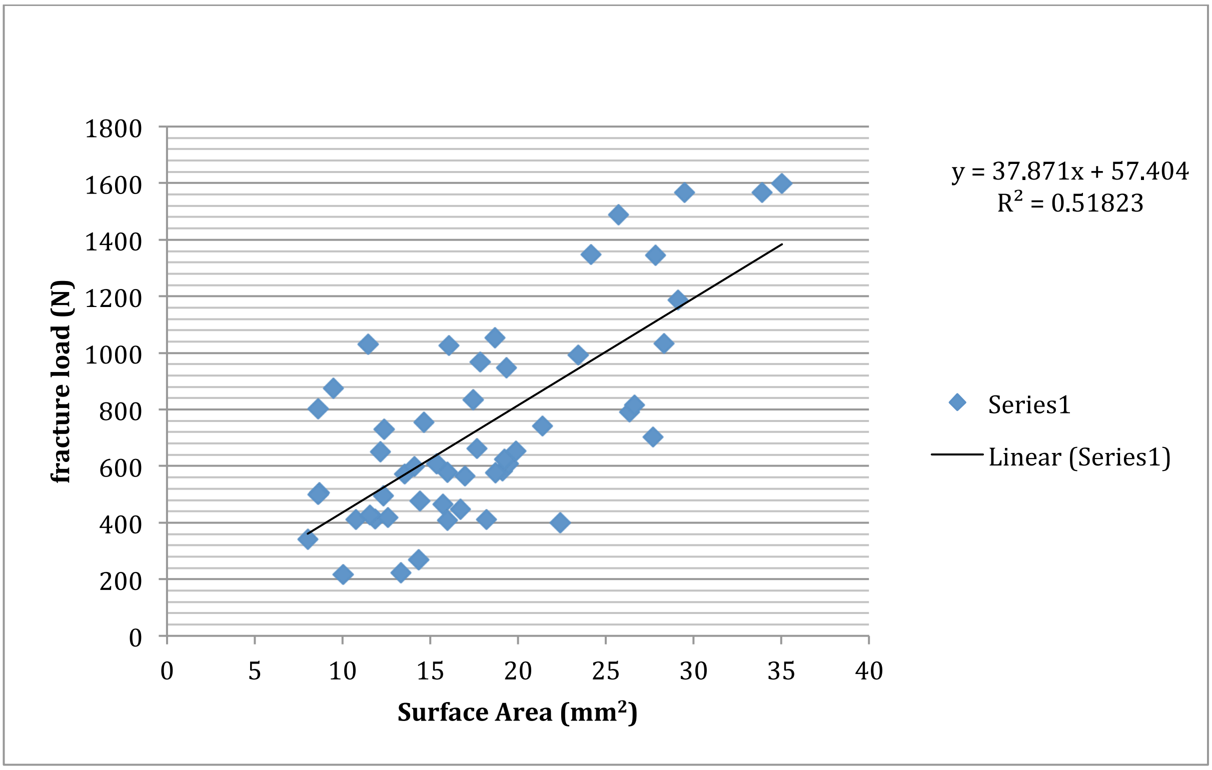


Figure 24: Correlation between Surface area (X-axis) and the fracture strength (Y-axis)

The association between this relationship and the data for each of the experimental groups is summarized in Appendix.

DISCUSSION

6.1 Selection of teeth

Upper premolars were chosen for this study their anatomic shape increases the tendency towards separation of the cusps and renders them more susceptible to cusp fracture during mastication[46, 72] This is a significant clinical problem for a tooth in the aesthetic zone.

In a retrospective clinical report, premolars were found to be the most frequently fractured teeth.[162] The risk of fracture was found to be greater in teeth in which the mesio-distal diameter is narrower than the bucco-lingual, such as maxillary and mandibular premolars and mesial roots of mandibular molars.[163, 164]

Mandibular premolars were found to have higher resistance to fracture compared to other premolars,[165] therefore they were excluded from this study.

In this study each group had teeth with similar dimensions in order to eliminate tooth dimension as a confounding factor.[19] There were no statistically significant differences between the lengths or the cross-sectional diameters between the groups. On the other hand, the age of the individuals from which the teeth were obtained was unknown because of the ethical requirement to de-identify the teeth collected. This variable might have an influence on the results because the pulp of a tooth decreases in volume with the passage of time,[166] and this may affect the surface area of the outer tooth structure.

In this study, teeth were stored in distilled water at room temperature. It is not clear whether all stored teeth had comparable dentine in terms of strength and hardness; also it is unclear if water, as storage medium may have influenced the properties of the dentine. However these effects were randomly distributed across all groups equally.

6.2 Surface area measurement

In our study, the teeth were carefully prepared without the core in place as suggested by Murphy *et al* [112] The methodology was simpler than alternative methods[110] that used interlocking trays to obtain a cast for the remaining tooth structure. On the other hand the preparation of teeth was slightly more difficult with this method as the core did not support thin sections of tooth structure during preparation and the making of impressions.

It has been reported that the cervical region of a tooth is exposed to the greatest stress, irrespective of the type of restoration or preparation design.[50, 167] In a study to investigate the stress distribution in a 3-D model of first maxillary premolar by using FEA,[168] the greatest compressive stress was found at the dentino-enamel junction in the cervical area (about –200 MPa), while the greatest tensile stress was found at the buccal cusp (about +3 MPa) and in the central fossa (about +28 MPa). Therefore the surface area for the remaining dentine was measured in this study at 1mm above the finish line in the cervical area where the greatest stresses are believed to concentrate.

In this study, hand instruments were used to prepare the root canal. Rotary instruments of different tapers used during the instrumentation, promote a more tapered root canals with less dentine cervically. The greater the amount of dentine removed during the preparation, the weaker the dental structure is, thus predisposing the root to fracture.[19] A study by Zamin *et al* [38] revealed that when the cervical preparation was performed with the highest taper (#70/ 0.12), the roots were more susceptible to fracture, in contrast to those that did not receive cervical preparation. This is of importance due to the increase use of the more tapered rotary instruments nowadays.

In this study there was a very strong correlation (r= 0.72) between the remaining surface area and the fracture resistance. This result support the previous findings that maximal thickness of axial tooth structure at the crown margin is necessary to resist fracture.[39, 52, 127] On the other hand one study by Sorensen *et al* [7] found that the thickness of the axial tooth structure at the crown margin does not affect fracture resistance and there was no correlation between the thickness of tooth structure and the failure threshold. This could be attributed to the methodology used in that study where they tested maxillary central incisors with post crowns.

Clearly surface area values decreased with the increase of the number of missing walls. Curiously when the palatal was the only remaining surface (group 10), this accounted for the lowest mean surface area among all other groups, but not the lowest mean fracture strength. The fact that this group had significantly higher strength than groups 8 and 9, supports the ides of strategic importance of the location of the remaining tooth structure.

6.3 Influence of the amount of remaining coronal tooth structure on the fracture resistance

The longevity of endodontically-treated teeth is difficult to evaluate because of the many inter-related factors. The amount of remaining coronal tooth structure prior to the final restoration could be one of the most important factors that has not widely been investigated in clinical studies, although it is arguably more important than other reported factors such as post material and design and cement and core material.[145]

A study by ElAyouti *et al* [42] showed that when the remaining wall thickness was 3 mm, composite restoration with cusp coverage significantly increased the fracture resistance of premolar teeth compared to those restored without cusp coverage. Even when the wall thickness was 1.5 and 2.0 mm similar results were observed. The results were comparable to that of intact teeth.

Few studies have assessed the amount of residual tooth structure. Residual dentine thickness after preparation for Cerec crowns in vital posterior teeth has been reported.[169] They concluded that the mean residual dentine thickness between the axial wall and pulp chamber varied between 0.47 and 0.70 mm in posterior teeth.

The thickness of remaining dentine following various preparations on a maxillary second premolar with an endodontic access and a moderate sized amalgam restoration has been reported.[170] Following preparation for a ceramo-metal or all-ceramic crown the thinnest sections of remaining tooth structure were 0.8 mm and 0.3 mm, respectively.

This study compared the fracture resistance of endodontically-treated teeth with one, two or three walls to those with four walls of remaining coronal tooth structure with the aim to represent the clinical situations of teeth with less than ideal ferrule.

All teeth were crowned in this study, to standardize the restorative technique rendering the effect of the crown on stress distribution on the tooth secondary to the influence that the remaining tooth structure had on the resistance to fracture under occlusal load.[39] This is consistent with other studies, which found that the structural strength of a tooth depends mainly on the amount of sound dentine available to support and retain the restorations.[39, 52, 127]

6.4 Influence of the remaining coronal tooth structure location on the fracture resistance:

In a previous study by Salameh *et al* [27] using mandibular molars, fracture resistance values were highly dependent on the number of remaining coronal walls, but the presence of a post had no effect on fracture resistances.

In this study among all groups; the groups with missing palatal walls showed the lowest fracture resistance in comparison to other groups in the same category. Among the groups with 2 missing walls, the palatal wall was as effective as circumferential axial wall in providing fracture resistance to the force applied. Among the groups with 3 missing walls, the combination between missing palatal and one proximal showed significantly lowest fracture resistance values than its category. This can be explained by the findings of Nam *et al* [28] when looking at the effect of the number of residual walls on fracture resistances, failure patterns, and photoelasticity of simulated premolars restored with or without fiber-reinforced composite posts. In the no-post group, high levels of stress were produced in the remaining internal tooth structure along the canal space. As the number of walls decreased to zero, a higher intensity of stress was noted in the lingual side of crown and the CEJ area.

The group with only the palatal wall remaining in this study showed the highest fracture resistance value among groups with four missing wall although it had the smallest surface area of remaining dentine. This indicates the importance of the palatal wall in resisting forces. On the other hand, a remaining buccal wall showed the lowest mean fracture resistance among all samples rendering it the least favorable situation even though this group did not have the lowest remaining dentine surface area.

In this study the fracture resistances of endodontically-treated upper premolars restored with composite resin core and full metal crowns, were affected by the number and the location of residual walls. This is in accordance with the results of FEA study by Nam *et al*.[28] who suggested that a 2-mm ferrule should be provided at least on the buccal and lingual wall.[100] This matter is still not entirely resolved as the site of the missing coronal wall did not have a significant effect on the fracture resistance of endodontically-treated teeth in other studies.[32]

It is possible that the direction of loading is a critical factor. This study used a static load from the palatal direction on the buccal cusp. The teeth tended to bend buccally with a fulcrum situated on the buccal surface. A palatal coronal wall may act as a critical factor to resist the displacement of the crown. Thus, fracture resistances of teeth without a palatal wall were the lowest among the tested groups.

6.5 Fracture resistance values

In terms of fracture resistance, the reported values differ between human teeth specimens depending on the conditions of teeth and experimental designs.[28] It is likely that variation in study design accounts for differences in reported outcomes. Variation between studies includes differences in: tooth type; tooth size; preparation design; restorative procedures; dental materials used; thermocycling and loading protocols.[37, 160] Therefore, when comparing studies it is more important to consider relative differences between the groups rather than absolute values.[19] The numbers are solely a basis for comparisons between the different experimental groups and cannot be transferred directly to the true clinical situation. Processing may have weakened the teeth and thus the actual forces required to create failure may be much higher *in vivo*.[19]

The forces placed on the dentition during normal masticatory function are generally small compared to the maximal biting force. For women, maximum biting forces in the first and second premolar areas of 178.54 ±77.20N and 206.01 ±86.52 N respectively have been reported, while for men corresponding forces of 254.08 ±72.20 N and 291.36 ±57.29N have been described[171]. In another study by Lepley *et al* [172] the men tended to have higher bite forces at the premolars 373.8 ± 102.6 N compared with 314.7 ± 96.5 N in women. Therefore, in interpreting results 400N might be considered as a level below which a premolar tooth is too weak to withstand normal biting force.

For the control group in this study (with only an occlusal access preparation) the mean fracture load was more than four times greater that this threshold (1380 ±393.9 N) which is entirely consistent with the common observation that maxillary premolars do not commonly fracture in these circumstances. A fracture strength of this magnitude is similar to strengths reported in other studies of maxillary premolars, where the mean fracture resistance values of 1,302.5N,[173] 828.17±226.63N[39] and 732.8 ±239.68N [21] have been reported for the intact control group.

Groups 2 (OPx), 4 (OB),5 (MOD),6 (BOP),7 (BOPx),and 10 (MODB) also displayed fracture resistances that were greater than the maximum reported loads. Groups 3 (OP), 8 (POPx), 9 (MODP) and 11 (BOPPx), however, showed fracture resistance values in the range of maximal biting loads but greater than physiological masticatory forces. However, experimental conditions in this study did not identically duplicate conditions in the mouth, since maxillary premolars are subjected to a mixture of shear and compressive forces, but some clinical relevance for data of this type has been suggested.[37]

Group 1 (O) with **four remaining coronal dentine walls** had a significantly higher fracture resistance than the groups with only one, two or three walls of remaining coronal dentine. These findings are supported Nissan *et al* [39] where teeth with remaining coronal structure showed higher load fracture (828.17 ±226.63 N) compared to teeth with no remaining coronal structure (616.15 ± 222.6 N).

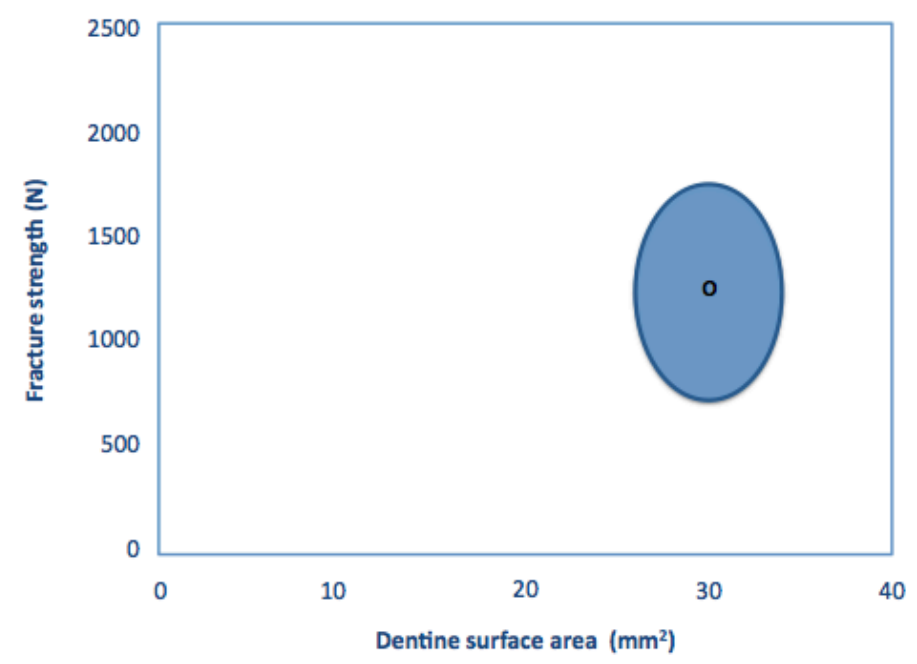


Figure 25: Plot chart to show the surface area and the fracture resistance values for group1 (Oclussal). The area showing the mean value±1 standard deviation.

Among the groups with **three remaining dentine walls** the lowest mean fracture strength value was 500.4±90.21N for group 3 (OP), which was significantly lower than the other groups in this category (Figure 26). Higher values were reported in a previous study[39] of first maxillary premolars with missing palatal walls (782.57±182.20N). These values were higher (but not significantly) than the comparison group with missing buccal walls (730±214.17 N). On the other hand the study differed significantly when threaded tapered posts 8 mm long were placed into the root next to the missing wall which would influence the reaction of the tooth to stresses and makes comparisons difficult

In another study[21] lower fracture strength values (489.66 ±149.45N) were recorded for endodontically-treated maxillary premolars with DO cavities compared with the strength values of 1142 ±307.9 N in this study. This difference is likely to be due to the restorative technique used. Teeth in the reported study were restored with composite resin with no cuspal coverage.

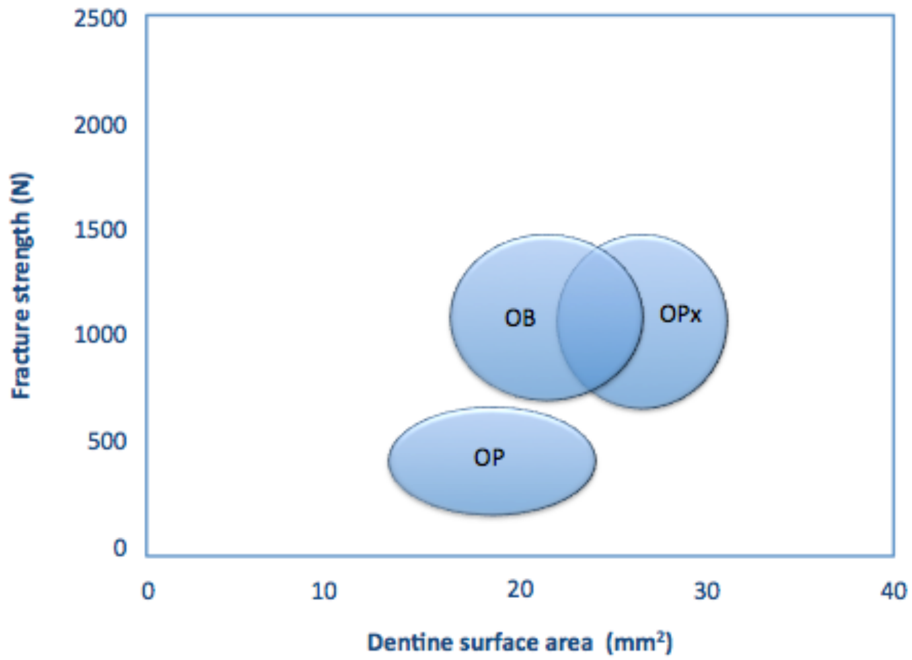


Figure 26: Plot graph showing the surface area and the fracture resistance values for the groups with three remaining dentine walls. The areas showing the mean values±1 standard deviation for each group.

In the groups with **two remaining dentine walls** mean fracture resistance value for group 5 (MOD) was significantly lower than the control group (O). These values were similar to another reported study[21] in which the mean fracture resistance value for teeth with MOD cavities was (723.93 ±147.18N) compared to 800.8±208.8N in this study. This agrees with Linn and Messer[174], who also demonstrated that endodontically-treated teeth with MOD cavities were severely weakened due to a loss of reinforcing structures, such as the marginal ridges and pulp chamber roof, causing the teeth to become more susceptible to fracture. In addition, a natural tooth usually contacts the adjacent teeth, and proper proximal contacts with the neighboring teeth, results in a decrease in the range and direction of natural tooth movement. Stress generated on a natural tooth can also be distributed to the adjacent teeth via proximal contact.[175] A study by Caplan *et al* [80] showed that RCT teeth with no or one proximal contact at access were lost at more than three times the rate of RCT teeth with two proximal contacts. Therefore the preservation of the marginal ridge is a preferred option in endodontically-treated maxillary premolars.[21] These findings are supported by Belli *et al* [176] who found that MOD cavity preparations reduced the fracture resistance of root-filled teeth. Other authors have also concluded that the preservation of the marginal ridge is a preferable option in maxillary endodontically-treated premolars.[37]

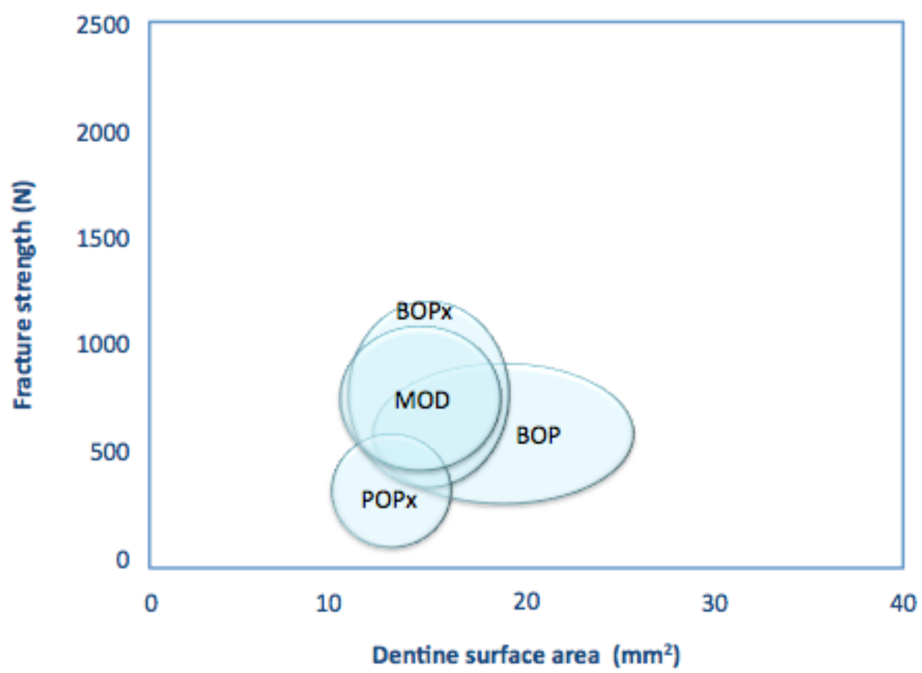


Figure 27: Plot graph showing the surface area and the fracture resistance values for the two remaining walls groups. The areas showing the mean values±1 standard deviation for each group.

In the groups with **only one remaining dentine wall** the mean fracture strength of samples in group 9 (MODP) was 344.7 ±91.25N. This group, with only the buccal cusp remaining, had the lowest mean load value of all groups, suggesting that the restorability of teeth in this situation is questionable. This value is lower than values reported by Kivanc *et al* [18] who found a mean failure load value of 920.33 ±162.24N for maxillary premolars restored with different post systems and composite cores with no crown. This situation is of clinical value as fracture analysis revealed that lingual cusps fracture more frequently in maxillary premolars under compressive loading[177]. Similarly, an *in vivo* study by Eakle *et al* [178] reported that the lingual cusps of maxillary premolars fractured more often than the buccal cusps. Therefore maxillary premolars with only one remaining buccal cavity wall can be a common clinical situation.

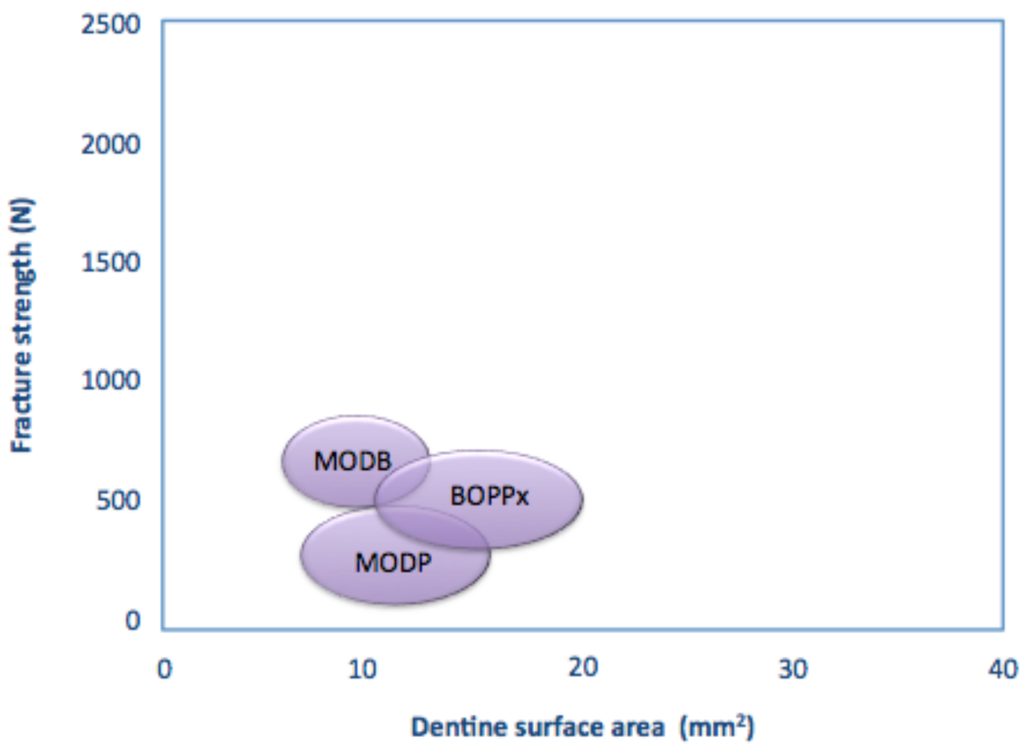


Figure 28: plot graph showing the surface area and the fracture resistance values for the one remaining wall groups. The areas showing the mean values±1 standard deviation for each group.

6.6 Mode of fracture

Cusp fracture patterns depend on the direction and amount of force applied, and the ability of the tooth to recover from the deformation. Force can be low and intermittent as in normal mastication; relatively high and consistent as in bruxism or; extremely high and sudden as in biting on a hard object or trauma.[20] The direction of the force application may influence the direction of the fractures.[38, 179, 180]

The failure mode of the tested teeth in the study by Nissan *et al* [39] showed that only teeth with remaining dentine after preparation were restorable following surgical crown lengthening and/or orthodontic extrusion, due to the coronal position of the fracture line.

In another study[160] the location of residual dentine appeared to influence the site of origin of the crack or fracture with the origin distributed more evenly across the proximal surface in specimens with a remaining proximal wall. In the group with a circumferential axial wall, the origin was usually located mid-proximal, or palatally. This could not be concluded in the current study as most fractures were oblique with no consistent relationship between the fracture and the the cervical line.. In the majority of specimens the crack or fracture was catastrophic, rendering the tooth unrestorable. This is in accordance to previous studies[34, 181] where an unfavorable subgingival facture location appeared to be associated with a history of endodontic treatment.

Interestingly, in the current study for two specimens in the control group the failure resulted from crown dislocation with a small tooth/core fracture supragingivally. This is consistent with the observed high fracture resistance in the control group, which clearly exceeded the retention of the crown in these two cases.

6.7 Limitations of the study

There are several problems associated with mechanical testing of extracted human teeth, including: sourcing sound, developmentally normal teeth that have not been damaged during extraction; tooth preparation without creating thermal or mechanical damage; and limitations of individual variations such as age; pulp size; the time elapsed after extraction; and the unknown effects of the storage conditions.[25, 28] Additional varriations can arise from different loading protocols and method of crown preparation.

In vitro research is limited in its ability to simulate the elasticity of the periodontal ligament, bone and tooth structure and the reproduction of the clinical environment including functional forces. Clinical trials are necessary to validate the results.[17]

6.8 Suggestions for further research

This study considered one class of teeth of unknown history with one type of load. Future studies could consider:

1. Different angles or directions of load. It would be interesting to know whether loading the palatal cusp instead of the buccal cusp affeced the strategic value of the remaining walls.
2. Different loads, investigating the effect of cyclic loading on fracture resistance and the mode of fracture of teeth could provide important information. It has been suggested that repeated loading and fatigue test can be more relevant to clinical situations.[29]
3. Other teeth

More importantly, long-term prospective clinical trials with accurate and reliable methods for the assessment of remaining tooth structure after crown preparation would provide clinicians with information as a basis for predicting the restorability of teeth[2].

CONCLUSION

Within the limitations of this in *vitro study* the following can be concluded for root canal treated upper premolars:

- The remaining dentine surface area decreases with the increase of the number of missing walls.
- There is a relationship between the remaining dentine surface area and the fracture strength.
- Residual dentine location influences the fracture resistance.
- The palatal wall has a major role in resisting forces.

REFERENCES

1. http://rsb.info.nil.gov.
2. Juloski, J., I. Radovic, C. Goracci, Z.R. Vulicevic, and M. Ferrari, *Ferrule effect: a literature review.* J Endod, 2012. **38**(1): p. 11-9.
3. Yalcin, E., M.C. Cehreli, and S. Canay, *Fracture resistances of cast metal and ceramic dowel and core restorations: a pilot study.* J Prosthodont, 2005. **14**(2): p. 84-90.
4. Trabert, K.C., A.A. Caput, and M. Abou-Rass, *Tooth fracture--a comparison of endodontic and restorative treatments.* J Endod, 1978. **4**(11): p. 341-5.
5. Naumann, M., F. Blankenstein, and C.R. Barthel, *A new approach to define defect extensions of endodontically treated teeth: inter- and intra-examiner reliability.* J Oral Rehabil, 2006. **33**(1): p. 52-8.
6. Tjan, A.H. and S.B. Whang, *Resistance to root fracture of dowel channels with various thicknesses of buccal dentin walls.* J Prosthet Dent, 1985. **53**(4): p. 496-500.
7. Sorensen, J.A. and M.J. Engelman, *Ferrule design and fracture resistance of endodontically treated teeth.* J Prosthet Dent, 1990. **63**(5): p. 529-36.
8. Isidor, F., K. Brondum, and G. Ravnholt, *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**(1): p. 78-82.
9. Saupe, W.A., A.H. Gluskin, and R.A. Radke, Jr., *A comparative study of fracture resistance between morphologic dowel and cores and a resin-reinforced dowel*

system in the intraradicular restoration of structurally compromised roots. Quintessence Int, 1996. **27**(7): p. 483-91.

10. al-Hazaimeh, N. and D.L. Gutteridge, *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**(1): p. 40-6.

11. Al-Wahadni, A. and D.L. Gutteridge, *An in vitro investigation into the effects of retained coronal dentine on the strength of a tooth restored with a cemented post and partial core restoration.* Int Endod J, 2002. **35**(11): p. 913-8.

12. Carter, J.M., S.E. Sorensen, R.R. Johnson, R.L. Teitelbaum, and M.S. Levine, *Punch shear testing of extracted vital and endodontically treated teeth.* J Biomech, 1983. **16**(10): p. 841-8.

13. Huang, T.J., H. Schilder, and D. Nathanson, *Effects of moisture content and endodontic treatment on some mechanical properties of human dentin.* J Endod, 1992. **18**(5): p. 209-15.

14. Ernst, C.P., K. Canbek, T. Euler, and B. Willershausen, *In vivo validation of the historical in vitro thermocycling temperature range for dental materials testing.* Clin Oral Investig, 2004. **8**(3): p. 130-8.

15. Brown, W.S., H.R. Jacobs, and R.E. Thompson, *Thermal fatigue in teeth.* J Dent Res, 1972. **51**(2): p. 461-7.

16. Gale, M.S. and B.W. Darvell, *Thermal cycling procedures for laboratory testing of dental restorations.* J Dent, 1999. **27**(2): p. 89-99.

17. Siso, S.H., F. Hurmuzlu, M. Turgut, E. Altundasar, A. Serper, and K. Er, *Fracture resistance of the buccal cusps of root filled maxillary premolar teeth restored with various techniques.* Int Endod J, 2007. **40**(3): p. 161-8.

18. Kivanc, B.H., T. Alacam, and G. Gorgul, *Fracture resistance of premolars with one remaining cavity wall restored using different techniques.* Dent Mater J, 2010. **29**(3): p. 262-7.

19. Zandbiglari, T., H. Davids, and E. Schafer, *Influence of instrument taper on the resistance to fracture of endodontically treated roots.* Oral Surg Oral Med Oral Pathol Oral Radiol Endod, 2006. **101**(1): p. 126-31.

20. Wu, Y., *Fracture resistance and fracture pattern of upper premolars with obturated canals and restored endodontic occlusal access cavities- an in-vitro study.* Journal of Biomedical research, 2010. **24**(6): p. 1-5.

21. Shahrbaf, S., B. Mirzakouchaki, S.S. Oskoui, and M.A. Kahnamoui, *The effect of marginal ridge thickness on the fracture resistance of endodontically-treated, composite restored maxillary premolars.* Oper Dent, 2007. **32**(3): p. 285-90.

22. Sherfudhin, H., J. Hobeich, C.A. Carvalho, M.N. Aboushelib, W. Sadig, and Z. Salameh, *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**(1): p. 28-33.

23. Yamada, Y., Y. Tsubota, and S. Fukushima, *Effect of restoration method on fracture resistance of endodontically treated maxillary premolars.* Int J Prosthodont, 2004. **17**(1): p. 94-8.

24. Loney, R.W., M.B. Moulding, and R.G. Ritsco, *The effect of load angulation on fracture resistance of teeth restored with cast post and cores and crowns.* Int J Prosthodont, 1995. **8**(3): p. 247-51.

25. Soares, C.J., E.C. Pizi, R.B. Fonseca, and L.R. Martins, *Influence of root embedment material and periodontal ligament simulation on fracture resistance tests.* Braz Oral Res, 2005. **19**(1): p. 11-6.

26. Naumann, M., A. Preuss, and M. Rosentritt, *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 odontologica Scandinavica, 2006. **64**(1): p. 31-6.
27. Salameh, Z., R. Sorrentino, F. Papacchini, H.F. Ounsi, E. Tashkandi, C. Goracci, and M. Ferrari, *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**(8): p. 752-5.
28. Nam, S.H., H.S. Chang, K.S. Min, Y. Lee, H.W. Cho, and J.M. Bae, *Effect of the number of residual walls on fracture resistances, failure patterns, and photoelasticity of simulated premolars restored with or without fiber-reinforced composite posts.* J Endod, 2010. **36**(2): p. 297-301.
29. Jung, S.H., K.S. Min, H.S. Chang, S.D. Park, S.N. Kwon, and J.M. Bae, *Microleakage and fracture patterns of teeth restored with different posts under dynamic loading.* J Prosthet Dent, 2007. **98**(4): p. 270-6.
30. Santana, F.R., C.G. Castro, P.C. Simamoto-Junior, P.V. Soares, P.S. Quagliatto, C. Estrela, and C.J. Soares, *Influence of post system and remaining coronal tooth tissue on biomechanical behaviour of root filled molar teeth.* Int Endod J, 2011. **44**(5): p. 386-94.
31. Mondelli, R.F., S.K. Ishikiriama, O. de Oliveira Filho, and J. Mondelli, *Fracture resistance of weakened teeth restored with condensable resin with and without cusp coverage.* J Appl Oral Sci, 2009. **17**(3): p. 161-5.
32. Arunpraditkul, S., S. Saengsanon, and W. Pakviwat, *Fracture resistance of endodontically treated teeth: three walls versus four walls of remaining coronal tooth structure.* J Prosthodont, 2009. **18**(1): p. 49-53.

33. Ayad, M.F., S.A. Bahannan, and S.F. Rosenstiel, *Influence of irrigant, dowel type, and root-reinforcing material on fracture resistance of thin-walled endodontically treated teeth.* J Prosthodont, 2011. **20**(3): p. 180-9.

34. Fennis, W.M., R.H. Kuijs, C.M. Kreulen, F.J. Roeters, N.H. Creugers, and R.C. Burgersdijk, *A survey of cusp fractures in a population of general dental practices.* Int J Prosthodont, 2002. **15**(6): p. 559-63.

35. Kelly, J.R., *Clinically relevant approach to failure testing of all-ceramic restorations.* J Prosthet Dent, 1999. **81**(6): p. 652-61.

36. Heydecke, G. and M.C. Peters, *The restoration of endodontically treated, single-rooted teeth with cast or direct posts and cores: a systematic review.* J Prosthet Dent, 2002. **87**(4): p. 380-6.

37. Oskoee, S.S., P.A. Oskoee, E.J. Navimipour, and S. Shahi, *In vitro fracture resistance of endodontically-treated maxillary premolars.* Oper Dent, 2007. **32**(5): p. 510-4.

38. Zamin, C., Y.T. Silva-Sousa, A.E. Souza-Gabriel, D.F. Messias, and M.D. Sousa-Neto, *Fracture susceptibility of endodontically treated teeth.* Dent Traumatol, 2012. **28**(4): p. 282-6.

39. Nissan, J., E. Barnea, D. Bar Hen, and D. Assif, *Effect of remaining coronal structure on the resistance to fracture of crowned endodontically treated maxillary first premolars.* Quintessence Int, 2008. **39**(8): p. e183-7.

40. Espevik, S., *Stress/strain behavior of dental amalgams.* Acta odontologica Scandinavica, 1978. **36**(2): p. 103-11.

41. Palamara, D., J.E. Palamara, M.J. Tyas, and H.H. Messer, *Strain patterns in cervical enamel of teeth subjected to occlusal loading.* Dent Mater, 2000. **16**(6): p. 412-9.

42. ElAyouti, A., M.I. Serry, J. Geis-Gerstorfer, and C. Lost, *Influence of cusp coverage on the fracture resistance of premolars with endodontic access cavities.* Int Endod J, 2011. **44**(6): p. 543-9.

43. Mohammadi, N., M.A. Kahnamoii, P.K. Yeganeh, and E.J. Navimipour, *Effect of fiber post and cusp coverage on fracture resistance of endodontically treated maxillary premolars directly restored with composite resin.* J Endod, 2009. **35**(10): p. 1428-32.

44. Khera, S.C., C.W. Carpenter, J.D. Vetter, and R.N. Staley, *Anatomy of cusps of posterior teeth and their fracture potential.* J Prosthet Dent, 1990. **64**(2): p. 139-47.

45. Ross, I.F., *Occlusal contacts of the natural teeth.* J Prosthet Dent, 1974. **32**(6): p. 660-7.

46. de Freitas, C.R., M.I. Miranda, M.F. de Andrade, V.H. Flores, L.G. Vaz, and C. Guimaraes, *Resistance to maxillary premolar fractures after restoration of class II preparations with resin composite or ceromer.* Quintessence Int, 2002. **33**(8): p. 589-94.

47. Asmussen, E., A. Peutzfeldt, and A. Sahafi, *Finite element analysis of stresses in endodontically treated, dowel-restored teeth.* J Prosthet Dent, 2005. **94**(4): p. 321-9.

48. Schmitter, M., P. Rammelsberg, J. Lenz, S. Scheuber, K. Schweizerhof, and S. Rues, *Teeth restored using fiber-reinforced posts: in vitro fracture tests and finite element analysis.* Acta Biomater, 2010. **6**(9): p. 3747-54.

49. Eraslan, O., F. Aykent, M.T. Yucel, and S. Akman, *The finite element analysis of the effect of ferrule height on stress distribution at post-and-core-restored all-ceramic anterior crowns.* Clin Oral Investig, 2009. **13**(2): p. 223-7.

50. Pierrisnard, L., F. Bohin, P. Renault, and M. Barquins, *Corono-radicular reconstruction of pulpless teeth: a mechanical study using finite element analysis.* J Prosthet Dent, 2002. **88**(4): p. 442-8.

51. Schmitter, M., P. Rammelsberg, O. Gabbert, and B. Ohlmann, *Influence of clinical baseline findings on the survival of 2 post systems: a randomized clinical trial.* Int J Prosthodont, 2007. **20**(2): p. 173-8.

52. Creugers, N.H., A.G. Mentink, W.A. Fokkinga, and C.M. Kreulen, *5-year follow-up of a prospective clinical study on various types of core restorations.* Int J Prosthodont, 2005. **18**(1): p. 34-9.

53. Ferrari, M., M.C. Cagidiaco, S. Grandini, M. De Sanctis, and C. Goracci, *Post placement affects survival of endodontically treated premolars.* J Dent Res, 2007. **86**(8): p. 729-34.

54. Cagidiaco, M.C., F. Garcia-Godoy, A. Vichi, S. Grandini, C. Goracci, and M. Ferrari, *Placement of fiber prefabricated or custom made posts affects the 3-year survival of endodontically treated premolars.* Am J Dent, 2008. **21**(3): p. 179-84.

55. Ferrari, M., A. Vichi, G.M. Fadda, M.C. Cagidiaco, F.R. Tay, L. Breschi, A. Polimeni, and C. Goracci, *A randomized controlled trial of endodontically treated and restored premolars.* J Dent Res, 2012. **91**(7 Suppl): p. 72S-78S.

56. Cavel, W.T., W.P. Kelsey, and R.J. Blankenau, *An in vivo study of cuspal fracture.* J Prosthet Dent, 1985. **53**(1): p. 38-42.

57. Steele, A. and B.R. Johnson, *In vitro fracture strength of endodontically treated premolars.* J Endod, 1999. **25**(1): p. 6-8.

58. Pilo, R., E. Shapenco, and I. Lewinstein, *Residual dentin thickness in bifurcated maxillary first premolars after root canal and post space preparation with parallel-sided drills.* J Prosthet Dent, 2008. **99**(4): p. 267-73.

59. Helfer, A.R., S. Melnick, and H. Schilder, *Determination of the moisture content of vital and pulpless teeth.* Oral Surg Oral Med Oral Pathol, 1972. **34**(4): p. 661-70.

60. Rivera, E.M. and M. Yamauchi, *Site comparisons of dentine collagen cross-links from extracted human teeth.* Arch Oral Biol, 1993. **38**(7): p. 541-6.

61. Schwartz, R.S. and J.W. Robbins, *Post placement and restoration of endodontically treated teeth: a literature review.* J Endod, 2004. **30**(5): p. 289-301.

62. Papa, J., C. Cain, and H.H. Messer, *Moisture content of vital vs endodontically treated teeth.* Endod Dent Traumatol, 1994. **10**(2): p. 91-3.

63. Sedgley, C.M., H.H. Messer, and T.D. Larson, *Are endodontically treated teeth more brittle?*

Part one: The restoration of non-vital teeth: structural, biological, and micromechanical issues in maintaining tooth longevity. Journal of endodontics, 1992. **18**(7): p. 332-5.

64. Dietschi, D., O. Duc, I. Krejci, and A. Sadan, *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**(9): p. 733-43.

65. Slutzky-Goldberg, I., H. Slutzky, C. Gorfil, and A. Smidt, *Restoration of endodontically treated teeth review and treatment recommendations.* Int J Dent, 2009. **2009**: p. 150251.

66. Caron, G.A., D.F. Murchison, R.B. Cohen, and J.C. Broome, *Resistance to fracture of teeth with various preparations for amalgam.* J Dent, 1996. **24**(6): p. 407-10.

67. Randow, K. and P.O. Glantz, *On cantilever loading of vital and non-vital teeth. An experimental clinical study.* Acta odontologica Scandinavica, 1986. **44**(5): p. 271-7.

68. Sim, T.P., J.C. Knowles, Y.L. Ng, J. Shelton, and K. Gulabivala, *Effect of sodium hypochlorite on mechanical properties of dentine and tooth surface strain.* Int Endod J, 2001. **34**(2): p. 120-32.

69. Pascon, F.M., K.R. Kantovitz, P.A. Sacramento, M. Nobre-dos-Santos, and R.M. Puppin-Rontani, *Effect of sodium hypochlorite on dentine mechanical properties. A review.* J Dent, 2009. **37**(12): p. 903-8.

70. Andreasen, J.O., B. Farik, and E.C. Munksgaard, *Long-term calcium hydroxide as a root canal dressing may increase risk of root fracture.* Dent Traumatol, 2002. **18**(3): p. 134-7.

71. Tang, W., Y. Wu, and R.J. Smales, *Identifying and reducing risks for potential fractures in endodontically treated teeth.* J Endod, 2010. **36**(4): p. 609-17.

72. Hansen, E.K., *In vivo cusp fracture of endodontically treated premolars restored with MOD amalgam or MOD resin fillings.* Dent Mater, 1988. **4**(4): p. 169-73.

73. Hansen, E.K., E. Asmussen, and N.C. Christiansen, *In vivo fractures of endodontically treated posterior teeth restored with amalgam.* Endod Dent Traumatol, 1990. **6**(2): p. 49-55.

74. Varlan, C., B. Dimitriu, V. Varlan, D. Bodnar, and I. Suciu, *Current opinions concerning the restoration of endodontically treated teeth: basic principles.* J Med Life, 2009. **2**(2): p. 165-72.

75. Katz, A., S. Wasenstein-Kohn, A. Tamse, and O. Zuckerman, *Residual dentin thickness in bifurcated maxillary premolars after root canal and dowel space preparation.* J Endod, 2006. **32**(3): p. 202-5.

76. Tamse, A., *Iatrogenic vertical root fractures in endodontically treated teeth.* Endod Dent Traumatol, 1988. **4**(5): p. 190-6.

77. Lang, H., Y. Korkmaz, K. Schneider, and W.H. Raab, *Impact of endodontic treatments on the rigidity of the root.* J Dent Res, 2006. **85**(4): p. 364-8.

78. Reeh, E.S., H.H. Messer, and W.H. Douglas, *Reduction in tooth stiffness as a result of endodontic and restorative procedures.* J Endod, 1989. **15**(11): p. 512-6.

79. Panitvisai, P. and H.H. Messer, *Cuspal deflection in molars in relation to endodontic and restorative procedures.* J Endod, 1995. **21**(2): p. 57-61.

80. Caplan, D.J., J. Kolker, E.M. Rivera, and R.E. Walton, *Relationship between number of proximal contacts and survival of root canal treated teeth.* Int Endod J, 2002. **35**(2): p. 193-9.

81. Felton, D.A., E.L. Webb, B.E. Kanoy, and J. Dugoni, *Threaded endodontic dowels: effect of post design on incidence of root fracture.* J Prosthet Dent, 1991. **65**(2): p. 179-87.

82. Trope, M. and H.L. Ray, Jr., *Resistance to fracture of endodontically treated roots.* Oral Surg Oral Med Oral Pathol, 1992. **73**(1): p. 99-102.

83. Assif, D., E. Oren, B.L. Marshak, and I. Aviv, *Photoelastic analysis of stress transfer by endodontically treated teeth to the supporting structure using different restorative techniques.* J Prosthet Dent, 1989. **61**(5): p. 535-43.

84. Joseph, J. and G. Ramachandran, *Fracture resistance of dowel channel preparations with various dentin thickness.* Fed Oper Dent, 1990. **1**(1): p. 32-5.

85. Caputo, A.A. and J.P. Standlee, *Pins and posts--why, when and how.* Dent Clin North Am, 1976. **20**(2): p. 299-311.

86. Sathorn, C., J.E. Palamara, D. Palamara, and H.H. Messer, *Effect of root canal size and external root surface morphology on fracture susceptibility and pattern: a finite element analysis.* J Endod, 2005. **31**(4): p. 288-92.

87. Goodacre, C.J. and K.J. Spolnik, *The prosthodontic management of endodontically treated teeth: a literature review. Part III. Tooth preparation considerations.* J Prosthodont, 1995. **4**(2): p. 122-8.

88. *The glossary of prosthodontic terms.* J Prosthet Dent, 2005. **94**(1): p. 10-92.

89. Mezzomo, E., F. Massa, and S.D. Libera, *Fracture resistance of teeth restored with two different post-and-core designs cemented with two different cements: an in vitro study. Part I.* Quintessence Int, 2003. **34**(4): p. 301-6.

90. Stankiewicz, N. and P. Wilson, *The ferrule effect.* Dent Update, 2008. **35**(4): p. 222-4, 227-8.

91. Stankiewicz, N.R. and P.R. Wilson, *The ferrule effect: a literature review.* Int Endod J, 2002. **35**(7): p. 575-81.

92. Cheung, G.S. and T.K. Chan, *Long-term survival of primary root canal treatment carried out in a dental teaching hospital.* Int Endod J, 2003. **36**(2): p. 117-28.

93. Ma, P.S., J.I. Nicholls, T. Junge, and K.M. Phillips, *Load fatigue of teeth with different ferrule lengths, restored with fiber posts, composite resin cores, and all-ceramic crowns.* J Prosthet Dent, 2009. **102**(4): p. 229-34.

94. Dikbas, I., J. Tanalp, E. Ozel, T. Koksal, and M. Ersoy, *Evaluation of the effect of different ferrule designs on the fracture resistance of endodontically treated maxillary central incisors incorporating fiber posts, composite cores and crown restorations.* J Contemp Dent Pract, 2007. **8**(7): p. 62-9.

95. Hinckfuss, S. and P.R. Wilson, *Effect of core material and restoration design on strength of endodontically treated bovine teeth: a laboratory study.* J Prosthodont, 2008. **17**(6): p. 456-61.

96. Pereira, J.R., A.L. Valle, F.K. Shiratori, J.S. Ghizoni, and M.P. Melo, *Influence of intraradicular post and crown ferrule on the fracture strength of endodontically treated teeth.* Braz Dent J, 2009. **20**(4): p. 297-302.

97. Cho, H., K.X. Michalakis, Y. Kim, and H. Hirayama, *Impact of interproximal groove placement and remaining coronal tooth structure on the fracture resistance of endodontically treated maxillary anterior teeth.* J Prosthodont, 2009. **18**(1): p. 43-8.

98. Libman, W.J. and J.I. Nicholls, *Load fatigue of teeth restored with cast posts and cores and complete crowns.* Int J Prosthodont, 1995. **8**(2): p. 155-61.

99. Varvara, G., G. Perinetti, D. Di Iorio, G. Murmura, and S. Caputi, *In vitro evaluation of fracture resistance and failure mode of internally restored endodontically treated maxillary incisors with differing heights of residual dentin.* J Prosthet Dent, 2007. **98**(5): p. 365-72.

100. Tan, P.L., S.A. Aquilino, D.G. Gratton, C.M. Stanford, S.C. Tan, W.T. Johnson, and D. Dawson, *In vitro fracture resistance of endodontically treated central incisors with varying ferrule heights and configurations.* J Prosthet Dent, 2005. **93**(4): p. 331-6.

101. Ng, C.C., H.B. Dumbrigue, M.I. Al-Bayat, J.A. Griggs, and C.W. Wakefield, *Influence of remaining coronal tooth structure location on the fracture resistance of restored endodontically treated anterior teeth.* J Prosthet Dent, 2006. **95**(4): p. 290-6.

102. Mahdavi Izadi, Z., E. Jalalian, A. Eyvaz Ziaee, L. Zamani, and B. Javanshir, *Evaluation of the effect of different ferrule designs on fracture resistance of maxillary incisors restored with bonded posts and cores.* J Dent (Tehran), 2010. **7**(3): p. 146-55.

103. de Oliveira, J.A., J.R. Pereira, A. Lins do Valle, and L.V. Zogheib, *Fracture resistance of endodontically treated teeth with different heights of crown ferrule restored with prefabricated carbon fiber post and composite resin core by intermittent loading.* Oral Surg Oral Med Oral Pathol Oral Radiol Endod, 2008. **106**(5): p. e52-7.

104. Dietschi, D., M. Romelli, and A. Goretti, *Adaptation of adhesive posts and cores to dentin after fatigue testing.* Int J Prosthodont, 1997. **10**(6): p. 498-507.

105. Hempton, T.J. and J.T. Dominici, *Contemporary crown-lengthening therapy: a review.* J Am Dent Assoc, 2010. **141**(6): p. 647-55.

106. Gegauff, A.G., *Effect of crown lengthening and ferrule placement on static load failure of cemented cast post-cores and crowns.* J Prosthet Dent, 2000. **84**(2): p. 169-79.

107. Meng, Q.F., Y.M. Chen, H.B. Guang, K.H. Yip, and R.J. Smales, *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**(6): p. 595-601.

108. Jotkowitz, A. and N. Samet, *Rethinking ferrule--a new approach to an old dilemma.* Br Dent J, 2010. **209**(1): p. 25-33.

109. Al-Omiri, M.K., A.A. Mahmoud, M.R. Rayyan, and O. Abu-Hammad, *Fracture resistance of teeth restored with post-retained restorations: an overview.* J Endod, 2010. **36**(9): p. 1439-49.

110. Bandlish, R.B., A.V. McDonald, and D.J. Setchell, *Assessment of the amount of remaining coronal dentine in root-treated teeth.* J Dent, 2006. **34**(9): p. 699-708.

111. McDonald, A. and D. Setchell, *Developing a tooth restorability index.* Dent Update, 2005. **32**(6): p. 343-4, 346-8.

112. Murphy, F., A. McDonald, A. Petrie, G. Palmer, and D. Setchell, *Coronal tooth structure in root-treated teeth prepared for complete and partial coverage restorations.* J Oral Rehabil, 2009. **36**(6): p. 451-61.

113. Davis, G.R., R.A. Tayeb, K.G. Seymour, and G.P. Cherukara, *Quantification of residual dentine thickness following crown preparation.* J Dent, 2012. **40**(7): p. 571-6.

114. Gillen, B.M., S.W. Looney, L.S. Gu, B.A. Loushine, R.N. Weller, R.J. Loushine, D.H. Pashley, and F.R. Tay, *Impact of the quality of coronal restoration versus the quality of root canal fillings on success of root canal treatment: a systematic review and meta-analysis.* J Endod, 2011. **37**(7): p. 895-902.

115. McLaren, J.D., C.I. McLaren, P. Yaman, M.S. Bin-Shuwaish, J.D. Dennison, and N.J. McDonald, *The effect of post type and length on the fracture resistance of endodontically treated teeth.* J Prosthet Dent, 2009. **101**(3): p. 174-82.

116. Monticelli, F., R. Osorio, A. Albaladejo, F.S. Aguilera, M. Ferrari, F.R. Tay, and M. Toledano, *Effects of adhesive systems and luting agents on bonding of fiber posts to root canal dentin.* J Biomed Mater Res B Appl Biomater, 2006. **77**(1): p. 195-200.

117. Soares, C.J., L.H. Raposo, P.V. Soares, P.C. Santos-Filho, M.S. Menezes, P.B. Soares, and D. Magalhaes, *Effect of different cements on the biomechanical*

behavior of teeth restored with cast dowel-and-cores-in vitro and FEA analysis. J Prosthodont, 2010. **19**(2): p. 130-7.

118. da Silva, N.R., L.H. Raposo, A. Versluis, A.J. Fernandes-Neto, and C.J. Soares, *The effect of post, core, crown type, and ferrule presence on the biomechanical behavior of endodontically treated bovine anterior teeth.* J Prosthet Dent, 2010. **104**(5): p. 306-17.

119. Salameh, Z., R. Sorrentino, H.F. Ounsi, W. Sadig, F. Atiyeh, and M. Ferrari, *The effect of different full-coverage crown systems on fracture resistance and failure pattern of endodontically treated maxillary incisors restored with and without glass fiber posts.* J Endod, 2008. **34**(7): p. 842-6.

120. Torbjorner, A. and B. Fransson, *A literature review on the prosthetic treatment of structurally compromised teeth.* Int J Prosthodont, 2004. **17**(3): p. 369-76.

121. Ray, H.A. and M. Trope, *Periapical status of endodontically treated teeth in relation to the technical quality of the root filling and the coronal restoration.* Int Endod J, 1995. **28**(1): p. 12-8.

122. Sterzenbach, G., M. Rosentritt, R. Frankenberger, S. Paris, and M. Naumann, *Loading Standardization of Postendodontic Restorations In Vitro: Impact of Restorative Stage, Static Loading, and Dynamic Loading.* Oper Dent, 2011.

123. Alsamadani, K.H., S.M. Abdaziz el, and S. Gad el, *Influence of different restorative techniques on the strength of endodontically treated weakened roots.* Int J Dent, 2012. **2012**: p. 343712.

124. Sorensen, J.A. and J.T. Martinoff, *Intracoronal reinforcement and coronal coverage: a study of endodontically treated teeth.* J Prosthet Dent, 1984. **51**(6): p. 780-4.

125. Robbins, J.W., *Guidelines for the restoration of endodontically treated teeth.* J Am Dent Assoc, 1990. **120**(5): p. 558, 560, 562 passim.

126. Goodacre, C.J. and K.J. Spolnik, *The prosthodontic management of endodontically treated teeth: a literature review. Part I. Success and failure data, treatment concepts.* J Prosthodont, 1994. **3**(4): p. 243-50.

127. Assif, D. and C. Gorfil, *Biomechanical considerations in restoring endodontically treated teeth.* The Journal of prosthetic dentistry, 1994. **71**(6): p. 565-7.

128. Fernandes, A.S. and G.S. Dessai, *Factors affecting the fracture resistance of post-core reconstructed teeth: a review.* Int J Prosthodont, 2001. **14**(4): p. 355-63.

129. Heydecke, G., F. Butz, and J.R. Strub, *Fracture strength and survival rate of endodontically treated maxillary incisors with approximal cavities after restoration with different post and core systems: an in-vitro study.* J Dent, 2001. **29**(6): p. 427-33.

130. Shillingburg HT, H.S., Whitsett L, Jacobi R, Brackett S. , *Fundamentals of fixed prosthodontics.* . 3rd ed1997, Chicago Quintessence Publishing.

131. Sorensen, J.A. and J.T. Martinoff, *Endodontically treated teeth as abutments.* J Prosthet Dent, 1985. **53**(5): p. 631-6.

132. Hunter, A.J., B. Feiglin, and J.F. Williams, *Effects of post placement on endodontically treated teeth.* J Prosthet Dent, 1989. **62**(2): p. 166-72.

133. Eskitascioglu, G., S. Belli, and M. Kalkan, *Evaluation of two post core systems using two different methods (fracture strength test and a finite elemental stress analysis).* J Endod, 2002. **28**(9): p. 629-33.

134. Kovarik, R.E., L.C. Breeding, and W.F. Caughman, *Fatigue life of three core materials under simulated chewing conditions.* J Prosthet Dent, 1992. **68**(4): p. 584-90.

135. Dorriz, H., M. Alikhasi, A. Mirfazaelian, and T. Hooshmand, *Effect of ferrule and bonding on the compressive fracture resistance of post and core restorations.* J Contemp Dent Pract, 2009. **10**(1): p. 1-8.

136. Monga, P., V. Sharma, and S. Kumar, *Comparison of fracture resistance of endodontically treated teeth using different coronal restorative materials: An in vitro study.* J Conserv Dent, 2009. **12**(4): p. 154-9.

137. Soares, P.V., P.C. Santos-Filho, L.R. Martins, and C.J. Soares, *Influence of restorative technique on the biomechanical behavior of endodontically treated maxillary premolars. Part I: fracture resistance and fracture mode.* J Prosthet Dent, 2008. **99**(1): p. 30-7.

138. Minto, A.M., W. Dinelli, T. Nonaka, and L.H. Thome, *[Comparative study of the fracture resistance of sound upper premolars and upper premolars restored with bonded amalgam].* Pesqui Odontol Bras, 2002. **16**(2): p. 121-6.

139. Gateau, P., M. Sabek, and B. Dailey, *Fatigue testing and microscopic evaluation of post and core restorations under artificial crowns.* J Prosthet Dent, 1999. **82**(3): p. 341-7.

140. Howdle, M.D., K. Fox, and C.C. Youngson, *An in vitro study of coronal microleakage around bonded amalgam coronal-radicular cores in endodontically treated molar teeth.* Quintessence Int, 2002. **33**(1): p. 22-9.

141. Gateau, P., M. Sabek, and B. Dailey, *In vitro fatigue resistance of glass ionomer cements used in post-and-core applications.* J Prosthet Dent, 2001. **86**(2): p. 149-55.

142. Mollersten, L., P. Lockowandt, and L.A. Linden, *A comparison of strengths of five core and post-and-core systems.* Quintessence Int, 2002. **33**(2): p. 140-9.

143. Vichi, A., M. Ferrari, and C.L. Davidson, *Influence of ceramic and cement thickness on the masking of various types of opaque posts.* J Prosthet Dent, 2000. **83**(4): p. 412-7.

144. Trushkowsky, R.D., *Esthetic and functional consideration in restoring endodontically treated teeth.* Dent Clin North Am, 2011. **55**(2): p. 403-10, x.

145. Robbins, J.W., *Restoration of the endodontically treated tooth.* Dent Clin North Am, 2002. **46**(2): p. 367-84.

146. Oliva, R.A. and J.A. Lowe, *Dimensional stability of silver amalgam and composite used as core materials.* J Prosthet Dent, 1987. **57**(5): p. 554-9.

147. Kijsamanmith, K., S. Timpawat, C. Harnirattisai, and H.H. Messer, *Micro-tensile bond strengths of bonding agents to pulpal floor dentine.* Int Endod J, 2002. **35**(10): p. 833-9.

148. Pilo, R., H.S. Cardash, E. Levin, and D. Assif, *Effect of core stiffness on the in vitro fracture of crowned, endodontically treated teeth.* J Prosthet Dent, 2002. **88**(3): p. 302-6.

149. Hofmann, N., N. Just, B. Haller, B. Hugo, and B. Klaiber, *The effect of glass ionomer cement or composite resin bases on restoration of cuspal stiffness of endodontically treated premolars in vitro.* Clin Oral Investig, 1998. **2**(2): p. 77-83.

150. Stavropoulou, A.F. and P.T. Koidis, *A systematic review of single crowns on endodontically treated teeth.* J Dent, 2007. **35**(10): p. 761-7.

151. Aquilino, S.A. and D.J. Caplan, *Relationship between crown placement and the survival of endodontically treated teeth.* J Prosthet Dent, 2002. **87**(3): p. 256-63.

152. Smales, R.J. and W.S. Hawthorne, *Long-term survival of extensive amalgams and posterior crowns.* J Dent, 1997. **25**(3-4): p. 225-7.

153. Scurria, M.S., D.A. Shugars, W.J. Hayden, and D.A. Felton, *General dentists' patterns of restoring endodontically treated teeth.* J Am Dent Assoc, 1995. **126**(6): p. 775-9.

154. Eckerbom, M. and T. Magnusson, *Restoring endodontically treated teeth: a survey of current opinions among board-certified prosthodontists and general dental practitioners in Sweden.* Int J Prosthodont, 2001. **14**(3): p. 245-9.

155. Sornkul, E. and J.G. Stannard, *Strength of roots before and after endodontic treatment and restoration.* J Endod, 1992. **18**(9): p. 440-3.

156. Edelhoff, D. and J.A. Sorensen, *Tooth structure removal associated with various preparation designs for anterior teeth.* J Prosthet Dent, 2002. **87**(5): p. 503-9.

157. Hussain, S.K., A. McDonald, and D.R. Moles, *In vitro study investigating the mass of tooth structure removed following endodontic and restorative procedures.* J Prosthet Dent, 2007. **98**(4): p. 260-9.

158. Fedorowicz, Z., B. Carter, R.F. de Souza, C. de Andrade Lima Chaves, M. Nasser, and P. Sequeira-Byron, *Single crowns versus conventional fillings for the restoration of root filled teeth.* Cochrane Database Syst Rev, 2012. **5**: p. CD009109.

159. Ha, U., *Interaction between enamel, porcelain and a gold alloy: An in vitro wear study*, 2011, Adelaide: Adelaide. p. 214.

160. Chapman, J., *Influence of Residual Coronal Dentine Location on the Fracture Resistance of Root-filled Maxillary Premolar Teeth Previously Restored with Direct Post-retained Cores and Cast Crowns*, in *Melbourne Dental School*2011, University of Melbourne: Melbourne. p. 120.

161. Yang, Z., Y.F. Hou, and X.B. Pan, *[Fracture resistance and failure modes of endodontically treated human teeth restored with four different post-core systems].* Hua Xi Kou Qiang Yi Xue Za Zhi, 2008. **26**(6): p. 633-5, 639.

162. Tamse, A., Z. Fuss, J. Lustig, and J. Kaplavi, *An evaluation of endodontically treated vertically fractured teeth.* J Endod, 1999. **25**(7): p. 506-8.

163. Katz, A. and A. Tamse, *A combined radiographic and computerized scanning method to evaluate remaining dentine thickness in mandibular incisors after various intracanal procedures.* Int Endod J, 2003. **36**(10): p. 682-6.

164. Lertchirakarn, V., J.E. Palamara, and H.H. Messer, *Patterns of vertical root fracture: factors affecting stress distribution in the root canal.* J Endod, 2003. **29**(8): p. 523-8.

165. Salis, S.G., J.A. Hood, E.E. Kirk, and A.N. Stokes, *Impact-fracture energy of human premolar teeth.* J Prosthet Dent, 1987. **58**(1): p. 43-8.

166. Bellucci, C. and N. Perrini, *A study on the thickness of radicular dentine and cementum in anterior and premolar teeth.* Int Endod J, 2002. **35**(7): p. 594-606.

167. Garhnayak, L., H. Parkash, D.K. Sehgal, V. Jain, and M. Garhnayak, *A Comparative Study of the Stress Distribution in Different EndodonticPost-RetainedTeeth with and without Ferrule Design-A Finite Element Analysis.* ISRN Dent, 2011. **2011**: p. 102329.

168. Borcic, J., R. Antonic, M.M. Urek, N. Petricevic, P. Nola-Fuchs, A. Catic, and I. Smojver, *3-D stress analysis in first maxillary premolar.* Coll Antropol, 2007. **31**(4): p. 1025-9.

169. Polansky, R., G. Arnetzl, M. Haas, C. Keil, G. Wimmer, and M. Lorenzoni, *Residual dentin thickness after 1.2-mm shoulder preparation for Cerec crowns.* Int J Comput Dent, 2000. **3**(4): p. 243-58.

170. Seow, L.L., C.G. Toh, and N.H. Wilson, *Remaining tooth structure associated with various preparation designs for the endodontically treated maxillary second premolar.* Eur J Prosthodont Restor Dent, 2005. **13**(2): p. 57-64.

171. Ferrario, V.F., C. Sforza, G. Serrao, C. Dellavia, and G.M. Tartaglia, *Single tooth bite forces in healthy young adults.* J Oral Rehabil, 2004. **31**(1): p. 18-22.

172. Lepley, C.R., G.S. Throckmorton, R.F. Ceen, and P.H. Buschang, *Relative contributions of occlusion, maximum bite force, and chewing cycle kinematics to masticatory performance.* Am J Orthod Dentofacial Orthop, 2011. **139**(5): p. 606-13.

173. Salameh, Z., R. Sorrentino, H.F. Ounsi, C. Goracci, E. Tashkandi, F.R. Tay, and M. Ferrari, *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**(7): p. 848-51.

174. Linn, J. and H.H. Messer, *Effect of restorative procedures on the strength of endodontically treated molars.* J Endod, 1994. **20**(10): p. 479-85.

175. Guichet, D.L., D. Yoshinobu, and A.A. Caputo, *Effect of splinting and interproximal contact tightness on load transfer by implant restorations.* J Prosthet Dent, 2002. **87**(5): p. 528-35.

176. Belli, S., A. Erdemir, M. Ozcopur, and G. Eskitascioglu, *The effect of fibre insertion on fracture resistance of root filled molar teeth with MOD preparations restored with composite.* Int Endod J, 2005. **38**(2): p. 73-80.

177. St-Georges, A.J., J.R. Sturdevant, E.J. Swift, Jr., and J.Y. Thompson, *Fracture resistance of prepared teeth restored with bonded inlay restorations.* J Prosthet Dent, 2003. **89**(6): p. 551-7.

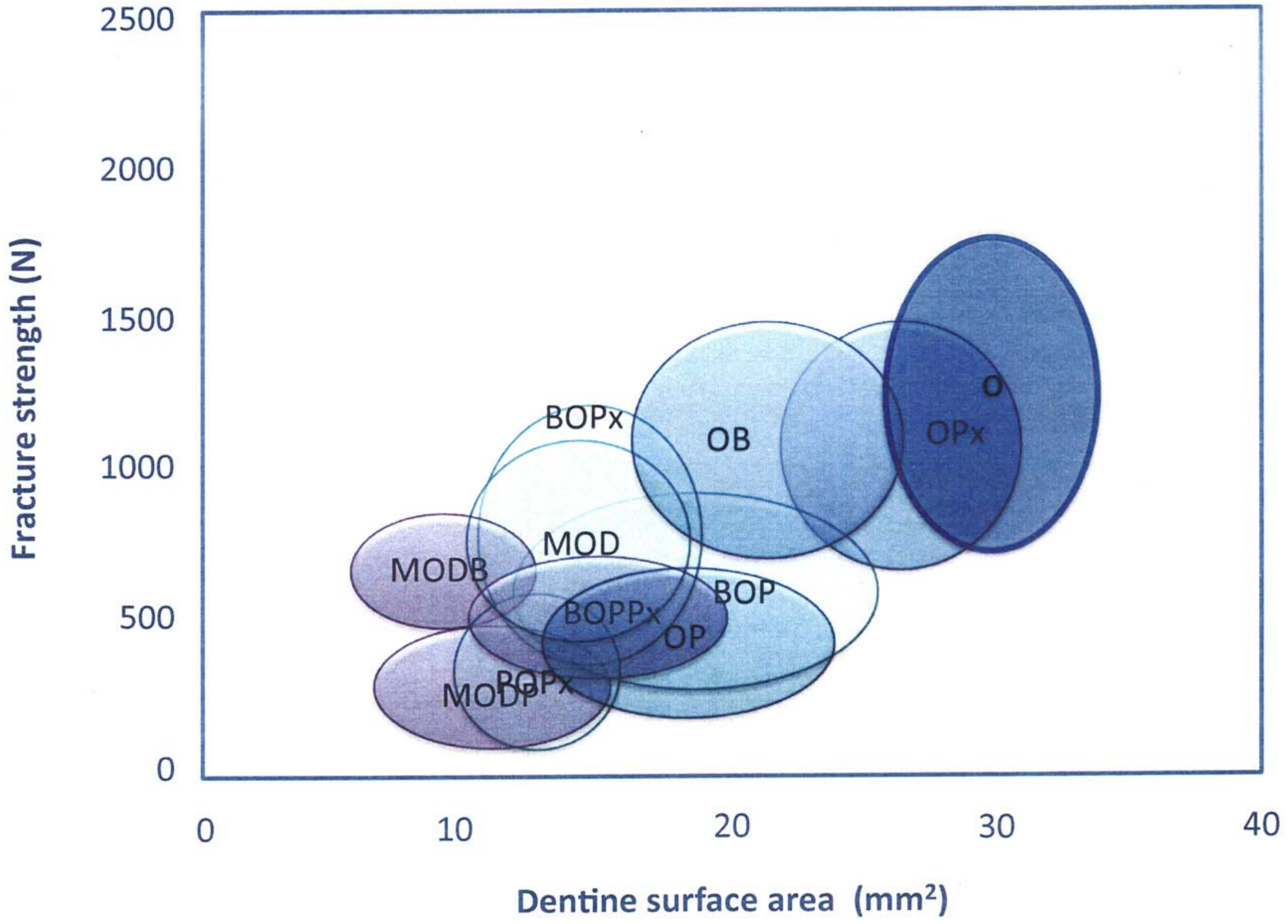
178. Eakle, W.S., E.H. Maxwell, and B.V. Braly, *Fractures of posterior teeth in adults.* J Am Dent Assoc, 1986. **112**(2): p. 215-8.

179. Teixeira, F.B., E.C. Teixeira, J.Y. Thompson, and M. Trope, *Fracture resistance of roots endodontically treated with a new resin filling material.* J Am Dent Assoc, 2004. **135**(5): p. 646-52.

180. Lertchirakarn, V., A. Timyam, and H.H. Messer, *Effects of root canal sealers on vertical root fracture resistance of endodontically treated teeth.* J Endod, 2002. **28**(3): p. 217-9.

181. Lagouvardos, P., P. Sourai, and G. Douvitsas, *Coronal fractures in posterior teeth.* Oper Dent, 1989. **14**(1): p. 28-32.

Appendix


Fracture strength (N)
2500
2000
1500
1000
500
0
0
10
20
30
40
Dentine surface area (mm²)
BOPx
OB
O
OPx
MOD
MODB
BOP
BOPPx
OP
BOPx
MODP