Biomechanical Considerations for Endocrowns in Restoring Endodontically Treated Teeth

By

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All the jointly-authored publications which form part of the thesis are derived from my Ph.D research. I performed all the experimental work, produced all the results and draft of the papers, dealt with all the review processes and other aspects of the publications. As it was best practice, the publications process was done under the guidance and help of my supervisors (or co-authors). To acknowledge my contribution as the lead author of the papers, I am the first named author in the publications. Details of the published papers/posters derived from my Ph. D work are provided in this thesis.

List of Publications

The following is a list of publications that shows one journal paper already published, one journal paper under review, in addition to three posters and two oral presentations that have been presented in international and local conferences/symposiums.

Journal papers:

HASSOUNEH, L., JUM'AH, A. A., FERRARI, M. & WOOD, D. J. 2020. Post-fatigue fracture resistance of premolar teeth restored with endocrowns: An in vitro investigation. *Journal of Dentistry,* 100**,** 103426. (Published)

HASSOUNEH, L., JUM'AH, A. A., FERRARI, M. & WOOD, D. J. Evaluation of marginal and internal fit of endocrowns fabricated from different CAD/CAM materials: A micro-computed tomography study. Operative Dentistry, (under second review)

Posters and oral presentations:

HASSOUNEH, FERRARI, M. & WOOD, D. J. Mechanical evaluation of endodontically treated premolars restored with endocrowna: 3D finite element analysis (Methodology). Presented at the 20th Scientific Congress of the Asian Pacific Endodontic Confederation (APEC 2019). Istanbul, Turkey. (Poster)

HASSOUNEH, FERRARI, M. & WOOD, D. J. Endocrown restorations: A review of clinical studies. Presented at the British Society for Oral and Dental Research conference (BSODR 2019). Leeds, UK. (Poster)

HASSOUNEH, FERRARI, M. & WOOD, D. J. Biomechanical considerations for endocrowns in restoring endodontically treated teeth. Presented at the University of Leeds, Dental School Research Day 2019. (Poster)

Fracture strength, stress distribution, and fitting accuracy of endocrowns using different CAD/CAM materials (preliminary results). Oral presentation at the Oral Biology divisional meeting, School of Dentistry, Leeds 2020.

Mechanical behaviour and fitting accuracy of endocrowns using different CAD/CAM materials. Oral presentation at the Bragg PhD Colloquium, University of Leeds 2021.

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Abstract

Background: Endodontically treated teeth have an increased risk of biomechanical failure because of significant loss of tooth structure. The ideal restorative technique and material for such teeth is always a challenge for the clinician.

Aims: The aim of this project was to evaluate the effect of using different dental CAD/CAM materials on the biomechanical behaviour of endodontically treated teeth restored with a new technique named endocrown.

Methodology: In this study, a thorough comparison of endocrown restorations fabricated from new types of all-ceramic, resin based composite and zirconia dental restorative materials through a series of systematic tests on human permanent premolars was performed. An extensive thermal and mechanical cyclic testing, static mechanical loading, micro-computed tomography analysis, scanning electron microscopy, optical profilometry, and finite element analysis evaluated the efficiency of endocrowns in terms of their mechanical properties and behaviour, fitting accuracy and stress distribution pattern.

Results: The current study reported significant effects for material selection along with restoration design and remaining sound tooth structure on the restoration efficiency of endodontically treated teeth. A significant interaction between restoration design and material type was observed, in which resin-based composite resulted in highest fracture strength among endocrowns, however all materials tested were able to survive dynamic thermo-mechanical fatigue testing simulating 2.5 years of clinical service. Monolithic translucent zirconia resulted in the highest number of catastrophic failures in restored teeth. The stress distribution pattern in the studied models revealed that the use of glass ceramics with endocrowns could enhance their long term bonding efficiency and retention, while resin composite endocrowns present a lower risk of catastrophic failure. Glass ceramics showed superior fitting accuracy and exhibited the smoothest and most homogenous fitting surface's roughness profile.

Conclusions: The mechanical behaviour, stress distribution and adaptation of resin based composite and glass ceramic endocrowns were clinically acceptable providing sufficient amount of sound tooth structure is preserved.

Zirconia endocrowns should be avoided with premolar teeth owing to the low fracture resistance and high risk of catastrophic failures. Endocrowns are not recommended in cases with no remaining buccal and lingual coronal walls.

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List of main abbreviations

σ_{MC} : Mohr–Coulomb stress ratio

σ_{max}: Maximum tensile principal stress

σ_{min}: Minimum compressive principal stress

°C: degree Celsius

µm: micrometre

3D: Three dimensional

AIS: Average internal space ratio

ANOVA: Analysis of variance

CAD/CAM: Computer aided design / computer aided manufacturing

CEJ: Cemento-enamel junction

EDTA: Ethylenediamine tetraacetic acid

ET: Endodontically treated

ETT: Endodontically treated teeth

FEA: Finite element analysis

FOS: Factor of safety

FPD: Fixed partial dentures

FRC's: fibre reinforced composites

GP: Gutta-percha

GPa: GigaPascal

h: Hour

HDM: High density micronization

Hz: Hertz

IDS: Immediate dentine sealing

Kg: Kilogram

LDGC: Lithium disilicate glass ceramic

LDS: Lithium disilicate

MDP: 1-Methacryloyloxydecyl Dihydrogen Phosphate

Micro-CT: Micro computed tomography

mm: millimetre

MPa: MegaPascal

N: Newton

PCT: Prospective clinical trial

PDL: Periodontal ligament

PICN: Polymer-infiltrated ceramic network

RBC: Resin based composite

RCT: Randomized controlled trials

RCT: Retrospective clinical trial

ROI: Region of interest

s: Seconds

SD: Standard deviation

SEM: Scanning electron Microscopy

UCS: Ultimate compressive strength

UTS: Ultimate tensile strength

Y-TZP: Yttrium oxide-stabilized tetragonal zirconia polycrystal

Zir: Zirconia

Chapter 1
Introduction and Literature Review

1.1 General Introduction

The restoration of highly damaged endodontically treated teeth (ETT) continues to be a challenging procedure in restorative dentistry. Clinical data regarding the optimal restorative procedure or material for restoring such teeth are still debatable (Girotto et al., 2020, Wang et al., 2019, Carvalho et al., 2018). The restoration of ETT is usually more complicated than vital teeth because they have a larger risk of biomechanical failure and are more prone to fractures (Zarone et al., 2006, Tang et al., 2010, Torbjörner and Fransson, 2004).

The loss of structural integrity in ETT due to caries, trauma and extensive cavity preparation is the main cause for their reduction in stiffness and fracture resistance, rather than dehydration or physical changes in dentine itself (Chang et al., 2009, Papa et al., 1994, Sedgley and Messer, 1992). Another aspect is the loss of neurosensory feedback in non-vital teeth, which might decrease the protection of ETT during mastication (Randow and Glantz, 1986, Lander and Dietschi, 2008).

Factors affecting the longevity of endodontic treatment include the type of restorative material used and the appropriate restorative technique that conserves tooth structure (Ferrari et al., 2000). The remaining tooth structure's quality and integrity must be preserved carefully in order to provide a solid base for restoration and enhance the structural strength of the restored tooth (Assif et al., 2003, Linn and Messer, 1994, Johnson et al., 1976, Schwartz and Robbins, 2004, Dietschi et al., 2007, Slutzky-Goldberg et al., 2009).

Full coverage crowns with fibre post and cores are currently recommended for restoring damaged ETT (Schwartz and Robbins, 2004, Smith and Schuman, 1997, Dietschi et al., 2008, Goracci and Ferrari, 2011, Ferrari et al., 2012, Juloski et al., 2014b, Ferrari et al., 2017). This procedure can help the tooth-restoration gain continuum strength and increase its resistance to fracture (Dietschi et al., 2008, Grandini et al., 2005). However, in spite of all clinical success reported with the application of intra-canal posts (Balkenhol et al., 2007), this technique still has many disadvantages that should be considered. One of the drawbacks for post and core restorations is the need to remove additional sound tissue in order to fit the post into the root canal (Lazari et al., 2013). In addition, when the invasiveness of posts over sound tissues is assessed, the possibility of root perforation and root fracture related to long post placement should be considered (Zicari et al., 2012), (Figure 1). In fact, the biomechanical behaviour of ETT was shown to be affected by this restorative procedure (Roscoe et al., 2013).

Figure 1 A case showing root perforation in the upper second premolar root caused during post preparation and placement. (https://dentalclaim.co.uk.)

The new era of adhesive dentistry along with the introduction of all-ceramic crown materials with improved mechanical features (Van Meerbeek et al., 2001), in addition to the introduction of digital dentistry, particularly dental chairside computer aided design/ computer aided manufacturing (CAD/CAM) technology, has made it possible to reconstruct ETT with extreme coronal damage by an alternative post-free restoration named an endocrown. This technique acquires retention and stability by the use of adhesive bonding, along with the surface accessible inside the pulp chamber (Bindl and Mormann, 1999).

Pissis described the forerunner of the endocrown technique, presenting it as the 'mono-block porcelain technique' (Pissis, 1995). The terminology endocrown was presented for the first time as adhesive endodontic crowns in 1999 by Bindl and Mormann, and was described as total porcelain crowns fixed to posterior ETT (Bindl and Mormann, 1999). These monoblock restorations would extend to the internal part of the pulp chamber and on the cavity margins, hence, attaining macromechanical retention from the pulpal walls, and gaining microretention by the use of adhesive cementation (Lin et al., 2011, Bindl and Mormann, 1999). The predictability of this post-free core restoration is supported by strong evidence especially when a substantial amount of remaining dentine is available to support a crown restoration (Fokkinga et al., 2007).

Until now, no specific definition or description has been stated for endocrown restorations. Different authors have used different definitions especially regarding the amount of residual tooth structure and other significant characteristics like material selection and tooth preparation. Bindl and Mormann defined an endocrown as a preparation with "*a circular equigingival butt margin and a central retention cavity of the entire pulp chamber*" (Bindl and Mormann, 1999), (Figure 2). Biacchi et al. described it as "*a total porcelain crown fixed to ET posterior tooth, which is anchored to the internal part of the pulp chamber and to the cavity margins*" (Biacchi et al., 2013), while Bernhart et al., considered a preparation with only 2 mm of height reduction as an endocrown, if the tooth is non-vital and there is at least a 2 mm of height retention in the pulp chamber (Bernhart et al., 2010). However, the amount of remaining tooth structure, the preparation design of peripheral margins, the use of the pulp chamber cavity for macromechanical retention, or the amount of extention in the pulp canals are all variables with no clear guidelines available to date, and hence could influence the restoration retention and performance.

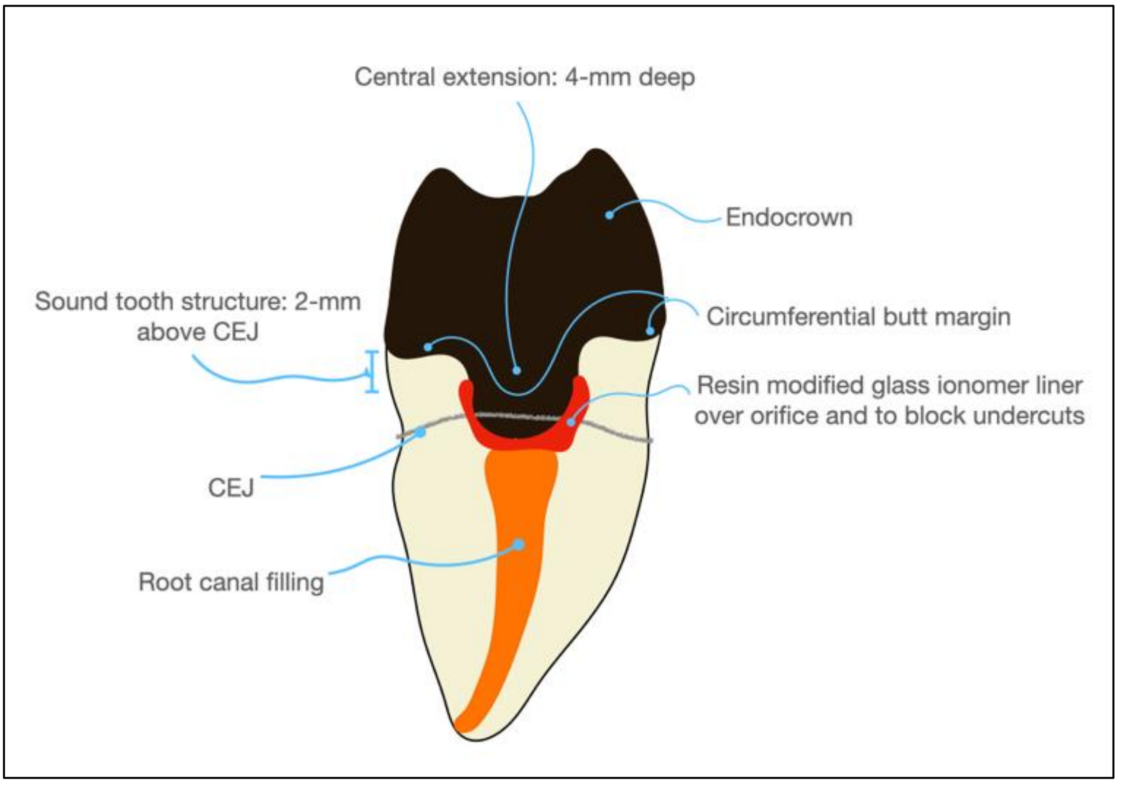


Figure 2 Schematic representation of endocrown preparation features.

The use of endocrowns in restoring ETT has many advantages over conventional techniques. This technique is simply performed, requires less clinical time in comparison to conventional post retained crowns, costs less because less steps are involved, overcomes the patient's lack of available time, reduces the chance of procedural errors, and has high aesthetic features because it is made of monoblock ceramics (Figure 3). Several *in-vivo* (Bindl and Mormann, 1999, Otto, 2004, Otto and Mormann, 2015, Bernhart et al., 2010, Bindl et al., 2005) and *in-vitro* (Biacchi and Basting, 2012, Rocca et al., 2016a, Bankoglu Gungor et al., 2017, El-Damanhoury et al., 2015, Lise et al., 2017, Gresnigt et al., 2016b) studies investigated this type of restoration with varying results being reported.

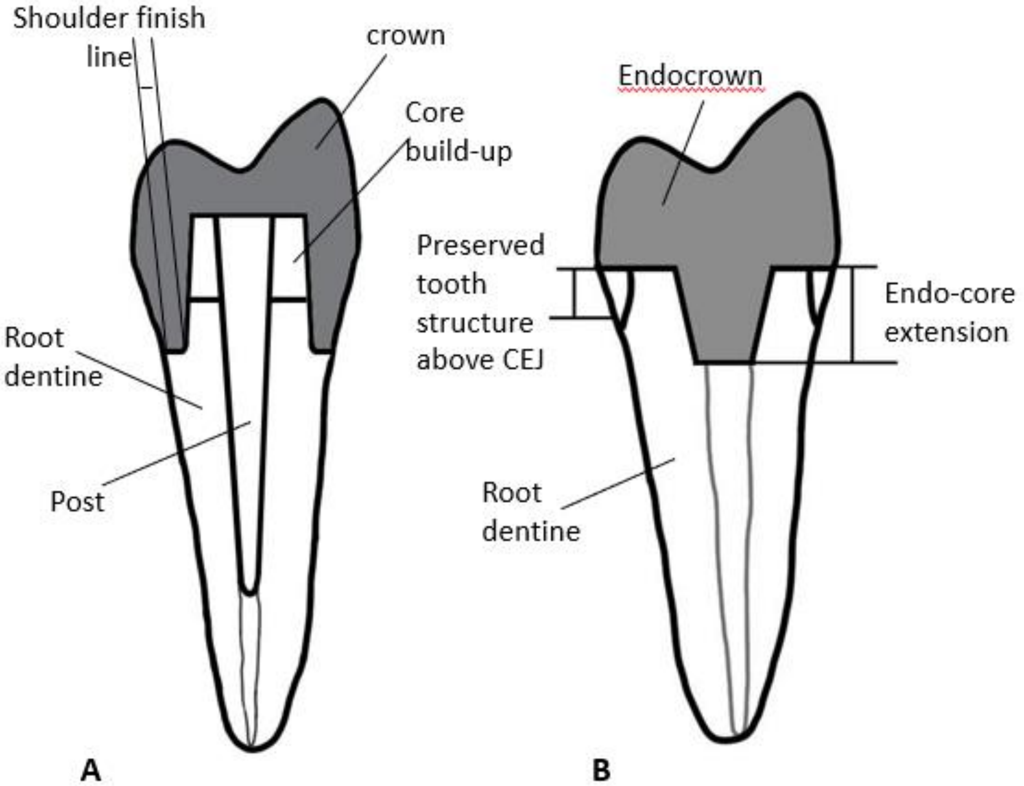


Figure 3 A schematic representative image illustrating the preparation and restoration design for A: post retained crowns, and B: endocrowns.

The trend towards using minimal invasive preparation designs like endocrowns in restoring ETT has been a hot topic of discussion in restorative dentistry lately, and the number of articles investigating it has widely increased during the past few years, yet this restorative technique remains controversial from many perspectives. One of the important factors to consider when applying a restorative treatment plan is the economical factor. Although endocrowns display several economic advantages as mentioned in the paragraph above, there is a lack of studies comparing the short and long term financial implications in comparison with other restorative techniques. Such studies should not only consider the direct treatment cost, but rather include all potential complications, side effects, patient satisfaction and the amount of maintenance required.

Overall, until now there is lack of clear data on the validity of endocrowns, in addition there is scarceness of clinical guidelines regarding the proper preparation design, material and tooth selection. Thus, this literature review aimed at identifying and summarising research articles conducted on various aspects related to endocrown restorations.

1.2 Literature Review

1.2.1 Search Methods

Electronic literature searches of medical databases were carried out from January 1995, the year endocrown was first introduced (Pissis, 1995) to May 2021 using the following key words: “Endocrown*” OR “endo crown*” OR “endodontic crown*” OR “adhesive crown*”. These key words were used alone or in combination with secondary key words like: “review”, “fracture resistance”, “fatigue”, “marginal adaptation”, “CAD/CAM materials”, “finite element analysis”, and “clinical trials”.

The electronic search included the following databases: MEDLINE via Pubmed, MEDLINE via OVID, EMBASE via OVID and Cochrane central register for controlled trials. Following the collection of articles from the databases, Endnote X7 software (Thompson Reuters, Philadelphia, PA, USA) was used to remove duplicate papers.

In-vitro, computer simulation and clinical Studies that evaluated endocrown restorations were identified according to the inclusion and exclusion criteria in Table 1. Full copies of all of the potentially relevant studies were extracted. The full-text papers were assessed. Papers that fulfilled the eligibility criteria were included.

Table 1 Eligibility criteria for study selection

Inclusion Criteria	**Exclusion criteria**
In-vitro, computer simulation and clinical studies	Case reports, literature reviews, pilot studies, letters to the editor, short commentaries, dissertations
Studies in which experiments were conducted on endodontically treated human permanent teeth	Animal studies
Studies including treatment with endocrown restorations	Studies reported in languages other than English
Types of endocrown material and cements clearly stated	
Studies published in English	

This comprehensive database search identified 100 relevant articles which were used to present the following review. This included 14 clinical studies, 62 *in-vitro* studies and 24 finite element studies.

The data from all reviewed articles were classified into two main sections: clinical studies and laboratory studies which included both *in-vitro* and computer simulation studies (finite element analysis). Next, laboratory studies were further categorised into subsections according to the main aspect studied in relation to endocrown restorations.

1.2.2 Clinical Studies

Fourteen clinical studies including two retrospective (Belleflamme et al., 2017, Borgia Botto et al., 2016, Hadzhigaev et al., 2017) and few prospective (Bindl et al., 2005, Otto and Mormann, 2015, Zimmerli et al., 2012, Zou et al., 2018, Fages et al., 2017, Bernhart et al., 2010, Hadzhigaev et al., 2017, Özyoney et al., 2013, Roggendorf et al., 2012, Liu and Ma, 2008) have so far investigated the clinical behaviour and outcome of ETT restored with endocrowns. The study design in addition to most important findings of all identified clinical studies are reported in (Table 2).

Table 2: the list of clinical studies investigating endocrowns, the study design and the most important findings. (PCS: Prospective clinical study, RCS: Retrospective clinical study, RCT: Randomised controlled trial).

Study	Type of study/ follow up period	Tooth type	Restoration groups	Materials used	Conclusions
Bindl & Mormann 1999	PCS/ 2 years	15 Molars and 4 Premolars	19 Endocrowns	feldspathic ceramic	Only one molar endocrown failed after 28 months because of recurrent caries. The overall clinical quality of the endocrowns was very good
Otto 2004	PCS/ 1 year	Molars and Premolars	10 Crowns with reduced stump preparations and 10 Endocrowns	feldspathic ceramic	Fractures or loss of retention were not observed. The method of placing all-ceramic reduced crowns and endocrowns chairside in one appointment can be implemented successfully

Study	Type of study/ follow up period	Tooth type	Restoration groups	Materials used	Conclusions
Bindl *et al*. 2005	PCS/ 55±15 months	145 Molars and 63 premolars	Classic crowns, Reduced crowns and Endocrowns	feldspathic ceramic	The survival of classic and reduced crowns was rated adequate for premolars and molars. Endocrowns appeared acceptable for molars but inadequate for premolars
Liu *et al*. 2008	PCS/ up to 5 years	61 molars	Endocrowns	Gold cast crowns; platinum cast crowns; nickel chromium alloys	Only two failures reported due to Secondary caries and mobility, no loose or debond crowns. With a survival rate of 96.6%
Bernhart *et al*. 2010	PCS/ 2 years	20 Molars	20 Endocrowns	feldspathic ceramic	Endocrowns reported good aesthetic and functional results

Study	Type of study/ follow up period	Tooth type	Restoration groups	Materials used	Conclusions
Zimmerli *et al*. 2012	PCS/ 3 years	42 teeth	42 Endocrowns luted with different adhesive cements	lithium disilicate ceramis	E.max CAD endocrowns showed good integration and perfect stability. An etch-and-rinse approach seems preferable to self-adhesive cements when ceramic restorations are to be luted in teeth with greatly reduced dental substance.
Roggendorf *et al.* 2012	PCS/ up to seven years	78 teeth	12 endocrowns and 66 other restorations	Vitablocks Mark II for CEREC or Procad	Three failures among endocrowns were reported with a success rate of 72.7%
Ozyoney *et al.* 2013	PCS/ 4 years	53 molars	53 Endocrowns	IPS Empress II ceramic	Endocrowns demonstrated promising results for restoring ET molars with a 92.5% success rate.

Study	Type of study/ follow up period	Tooth type	Restoration groups	Materials used	Conclusions
Otto & Mormann 2015	PCS/ 9-12 years	Molars and Premolars	25 endocrowns and 40 shoulder crowns	feldspathic ceramic	The survival of shoulder crowns on molars and premolars, as well as of endocrowns on molars, proved to be very acceptable, while the premolar endocrowns tended to show a higher risk for failure.
Borgia Botto *et al*. 2016	RCS (Case series) 8-19 years	Molars	11 Endocrowns	leucite glass-ceramic, Composite resin	Endocrowns showed a very good biomechanical and functional performance, and very acceptable longevity

Study	Type of study/ follow up period	Tooth type	Restoration groups	Materials used	Conclusions
Belleflamme *et al*. 2017	RCS/ 44.7 ± 34.6 months	Molars (56.6%) Premolars (41.4%) Canines (2.0%)	99 Endocrowns	Lithium-Disilicate (84.8%) Polymer-Infiltrated Ceramic Network (12.1%)	Endocrowns were shown to constitute a reliable approach to restore severely damaged molars and premolars
Fages *et al*. 2017	PCS/ 5-7 years	Molars	212 peripheral crowns and 235 endocrowns	feldspathic ceramic	This survival rate study reinforced the use of CAD/CAM full ceramic crowns and endocrowns on molars, showing a much more favourable survival rate for endocrowns.

Study	Type of study/ follow up period	Tooth type	Restoration groups	Materials used	Conclusions
Hadzhigaev *et al*. 2017	RCT/ 4 years	Distal abutment Molars	Three-unit FPD's with endocrown distal abutment and conventional three unit FPD	laboratory fibre reinforced composite resin	endocrown retained FPD's have a satisfactory performance for the 4 year evaluation period
Zou *et al*. 2018	PCS/ 3 years	Molars	321 Endocrowns	Monolithic zirconia	None of the 289 endocrowns failed during the observation period. Monolithic zirconia endocrowns can be considered a reliable restoration for endodontically treated molars with extensive coronal loss of substance.

The few clinical studies which investigated the clinical outcome of endocrowns reported very promising findings, however most of these studies are related to small sample size and/or observation time (Bindl et al., 2005, Bindl and Mormann, 1999, Otto and Mormann, 2015, Bernhart et al., 2010, Otto, 2004).

A clinical comparison between conventional crowns and endocrowns has been conducted by Bindl and Mormann and the results showed that the failure patterns differed mechanically (Bindl and Mormann, 1999). More adhesion loss failures were reported with endocrown restorations, whereas crown restorations reported no adhesion loss, and interestingly, the opposite was reported with ceramic material fractures. However, regardless of the previous differences, both types of restorations showed similar numbers of root fracture cases. The survival rate for endocrowns was 87% and 68% for molars and premolars respectively. Premolars were shown to fail more often than molars and it was concluded that this treatment is acceptable for molars but inadequate for premolars (Bindl et al., 2005). This was in agreement with Otto and Mormann 2015, where they reported a survival rate of 90% on molars and 75% on premolars for a study of 25 endocrown cases (Otto and Mormann, 2015).

However, in a recent retrospective study, an excellent survival rate of 99.0% after (44.7 ± 34.6 months) and 10-year Kaplan-Meier estimated survival rate of (98.8%) was recorded for lithium disilicate and PICN endocrowns constructed on molars and premolars. According to this study, severely damaged molars and premolars can be efficiently restored by endocrowns, even in cases of significant coronal tissue damage or the presence of occlusal risk factors, such as bruxism or unfavourable occlusal relationships (Belleflamme et al., 2017). In this study, premolars did not present any debonding failures, in contrast to what was reported by Bindl et al. in 2005 (Bindl et al., 2005). Endocrowns in this study were constructed by two different materials and immediate dentine sealing (IDS) with a bonding agent immediately following tooth preparation was used to improve adhesion (Magne et al., 2005). This might contribute to the better success rate than previous studies in terms of debonding (Bindl et al., 2005). However, the results of this study should be considered with caution due to several limitations in the study design, such as the short follow up period and limited number of samples. Therefore, more studies involving premolar teeth are highly recommended.

The promising findings from previous studies were also confirmed by other clinical studies. A study (Bernhart et al., 2010) reported two years survival rate of 90% for 20 cases. Fages et al. also reported high survival rates for endocrowns on posterior teeth. They analysed the clinical outcomes of CAD/CAM All-Ceramic crowns and endocrowns over a 7-year functional period. Only 6 failures were observed out of 447 restorations placed, resulting in an overall success rate of 98.66%. Only one of the six ceramic fractures appeared on an endocrown, while five appeared on peripheral crowns. Accordingly, this study revealed a much more favourable survival rate for endocrowns (Fages et al., 2017). Also, interestingly, a recent study reported very promising results for CAD/CAM monolithic zirconia endocrowns on molars with extensive coronal tissue loss for a clinical service period of 3 years (Zou et al., 2018). None of the 289 endocrowns included in this study failed during the observation period, and a high clinical rating criteria of 97.2% was reported.

Only one clinical study evaluated the effect of luting procedure on the performance of endocrown restorations (Zimmerli et al., 2012). This study included 42 lithium disilicate endocrowns that were luted using either etch-and-rinse adhesive with resin cement (group 1) or self-adhesive resin cement (group 2). Over the 36 months of observation, the first group experienced no debondings, while two debondings of endocrowns were observed in the second group. 84% of group 1 and 67% of group 2 showed a perfect marginal integrity. They recommended the use of the etch-and-rinse approach when luting ceramic restorations to teeth with extensive tissue loss (Zimmerli et al., 2012).

Whereas no Randomised Controlled Trials (RCT) could be identified for single unit endocrowns, one RCT investigating three-unit Fixed Partial Dentures (FPD) with endocrown abutments was identified (Hadzhigaev et al., 2017). This study showed that both classic and endocrown retained FPD’s had a satisfactory performance for the 4 year evaluation period, and they recommended a post-free solution for restoration of ETT even when the restoration is a short span bridge.

Endocrowns and other conventional restorations were compared in a systematic review and meta-analysis (Sedrez-Porto et al., 2016). According to the 3 clinical studies included in this review, endocrowns reported a success rate between 94% and 100%. The global analysis in posterior and anterior teeth revealed higher fracture strength for endocrowns compared to conventional treatments, however when only posterior teeth were analysed, no statistically significant differences between endocrowns and other restorations were reported (Sedrez-Porto et al., 2016). On the other hand, a more recent systematic review compared the success of endocrown restorations between molars and premolars (Thomas et al., 2020). They found similar success rates with no difference between molars and premolars. However, the previous findings should be interpreted with caution since the clinical studies included presented many limitations such as short observation period, low number of samples, and no control group. Therefore, it is still recommended that further studies are necessary to confirm their findings (Al-Dabbagh, 2020, Thomas et al., 2020).

The high survival rates and the promising findings from the available clinical studies to date on endocrowns are similar or even higher than the reported 5-year survival rates of all ceramic crowns, metal-ceramic crowns, and post-core retained crowns (Schmitter and Hamadi, 2011, Sailer et al., 2015). However, in addition to the insufficient number of clinical studies available on endocrowns, most of these studies are related to small sample size and/or short observation period (Bindl et al., 2005, Bindl and Mormann, 1999, Otto and Mormann, 2015, Bernhart et al., 2010, Otto, 2004), which induces the need for more comprehensive clinical studies. Also because of this limited number of studies, the different factors required to correct the clinical interpretations and decrease the failure rate remain unclear. In general, the level of scientific clinical evidence regarding endocrown restorations is considered insufficient. Accordingly, clinicians are highly reliant on the available *in-vitro* studies in order to reach to the best treatment planning, preparation design, tooth and material selection for endocrown restorations.

1.2.3 Laboratory Studies

Most of the reviewed articles investigating endocrowns are laboratory *in-vitro* studies (Tables 3-9). The majority of these articles used human posterior molars, some used premolars and very few used anteriors. A static load test where individual specimens are subjected to constant load until tooth fracture, followed by a comparison and analysis of maximum loads and patterns of fracture, was the most common test used in reviewed articles (Rayyan et al., 2019, Turkistani et al., 2020, Sağlam et al., 2021). The high single force application used in this test might simulate what occurs in case of trauma or some para-functional habits. However, *in-vitro* static testing does not mimic the clinical environment where teeth are subjected to thermal changes and repetitive mechanical loading, hence, the clinical significance of such tests has been questioned (Kelly, 1999). Therefore, studies including thermal, mechanical, or thermo-mechanical fatigue testing that will provide more clinically relevant data were conducted (Silva-Sousa et al., 2020, Hassouneh et al., 2020, Elashmawy et al., 2021). In addition to studies investigating the mechanical behaviour of endocrown restorations, some *in-vitro* studies also evaluated the marginal adaptation and internal fit of endocrown restorations. These studies used different laboratory techniques such as: Scanning Electron Microscope (SEM), Micro-CT, and methylene-blue dye solution with a stereomicroscope.

Besides *in-vitro* studies, computer simulation articles investigating endocrowns were also reviewed. These studies used the Finite Element Analysis (FEA) method, which is a method that can analyse complex structures and calculate the stress distribution within these structures (Dartora et al., 2018). The accuracy of the model used in this technique is what determines the accuracy of the results obtained. FEA can be useful in investigating different aspects related to endocrown restorations due to the enormous variability of the data received from *in-vitro* studies.

Data obtained from the reviewed laboratory studies were further categorised based on the main aspect that was investigated into following sections as follows: endocrown versus other restorations, type of teeth investigated, margin design, endo-core depth and design, occlusal thickness, cementation and materials used (Tables 3 to 9).

Table 3 A list of reviewed laboratory studies investigating Endocrown versus other restorations, classified according to the type of *in-vitro* study.

Type of test		Static load testing	Thermo-mechanical loading and static load testing	Fatigue loading	Finite element analysis	Marginal adaptation
Studies investigating Endocrown versus Post-core crowns	Anteriors	(Bankoglu Gungor et al., 2017)	(Ramirez-Sebastia et al., 2014, Silva-Sousa et al., 2020)		(Zarone et al., 2006, Dejak and Mlotkowski, 2018, Li et al., 2020)	

Type of test		Static load testing	Thermo-mechanical loading and static load testing	Fatigue loading	Finite element analysis	Marginal adaptation
	Premolars	(Chang et al., 2009, Atash et al., 2017) (Guo et al., 2016b)	(Forberger and Gohring, 2008, Hassouneh et al., 2020)	(Rocca et al., 2018, Rocca et al., 2016b)	(Lin et al., 2009, Lin et al., 2010, Lin et al., 2011, Lin et al., 2013, Caldas et al., 2018)	
	Molars	(Biacchi and Basting, 2012, Krance et al., 2018, Rayyan et al., 2019, Kassis et al., 2020)	(de Kuijper et al., 2020b, de Kuijper et al., 2019, Sedrez-Porto et al., 2020)	(Magne et al., 2014, Carvalho et al., 2016)	(Dejak and Mlotkowski, 2013, Helal and Wang, 2017, Dejak and Młotkowski, 2020, Lin et al., 2020)	(Hasanzade et al., 2020)

Table 4 A list of reviewed laboratory studies investigating different margin designs, classified according to the type of *in-vitro* study.

Type of test	Static load testing	Thermo-mechanical loading and static load testing	Fatigue loading	Finite element analysis	Marginal adaptation
Studies investigating different margin designs	(Taha et al., 2018b, Einhorn et al., 2017, Clausson et al., 2019)	(Ghoul et al., 2020, Silva-Sousa et al., 2020)		(Guo et al., 2016a)	

Table 5 A list of reviewed laboratory studies investigating the design and depth of endocrown central extension (endo-core), classified according to the type of *in-vitro* study.

Type of test	Static load testing	Thermo-mechanical loading and static load testing	Fatigue loading	Finite element analysis	Marginal adaptation
Studies investigating the endo-core depth and design	(Kanat-Erturk et al., 2018, Hayes et al., 2017, Ghajghouj and Tasar-Faruk, 2019)	(Lise et al., 2017, Dartora et al., 2018, de Kuijper et al., 2020a)	(Rocca et al., 2018)	(Gulec and Ulusoy, 2017, Dartora et al., 2018, Tribst et al., 2021a, Tribst et al., 2021b, Zhu et al., 2020)	(Rocca et al., 2018, Shin et al., 2017, Gaintantzopoulou and El-Damanhoury, 2016, Gurpinar and Tak, 2020, Topkara and Keleş, 2021, Hajimahmoudi et al., 2021)

Table 6 A list of reviewed laboratory studies investigating the occlusal thickness of endocrowns, classified according to the type of *in-vitro* study.

Type of test	Static load testing	Thermo-mechanical loading and static load testing	Fatigue loading	Finite element analysis	Marginal adaptation
Studies investigating the occlusal thickness of endocrowns	(Mörmann et al., 1998, Taha et al., 2018b, Haralur et al., 2020, Turkistani et al., 2020)			(da Fonseca et al., 2018, Lin et al., 2020)	

Table 7 A list of reviewed laboratory studies investigating the effect of remaining sound tooth structure, classified according to the type of *in-vitro* study.

Type of test	Static load testing	Thermo-mechanical loading and static load testing	Fatigue loading	Finite element analysis	Marginal adaptation
Studies investigating the effect of remaining tooth structure	(Hofsteenge and Gresnigt, 2021)			(Caldas et al., 2018, Zhu et al., 2017, Tribst et al., 2018, Li et al., 2020)	

Table 8 A list of reviewed laboratory studies investigating different cementation techniques, classified according to the type of *in-vitro* study.

Type of test	Static load testing	Thermo-mechanical loading and static load testing	Fatigue loading	Finite element analysis	Marginal adaptation
Studies investigating different cementation techniques	(El-Damanhoury and Gaintantzopoulou, 2016, Gregor et al., 2014, Daher et al., 2020, Ghajghouj and Tasar-Faruk, 2019)	(Kassem et al., 2020)			

Table 9 A list of reviewed laboratory studies investigating the use of different types of restorative materials, classified according to the type of *in-vitro* study.

Type of test/ Parameter tested	Static load testing	Thermo-mechanical loading and static load testing	Fatigue loading	Finite element analysis	Marginal adaptation
Studies investigating the use of different restorative materials	(El-Damanhoury et al., 2015, Gresnigt et al., 2016b, Aktas et al., 2018, Bankoglu Gungor et al., 2017, Skalskyi et al., 2018, Kanat-Erturk et al., 2018, Altier et al., 2018, Sağlam et al., 2021, Zheng et al., 2020, Skalskyi et al., 2020)	(Lise et al., 2017, Taha et al., 2018a, Ramirez-Sebastia et al., 2014, Hassouneh et al., 2020, Sedrez-Porto et al., 2019, El Ghoul et al., 2019a, Acar and Kalyoncuoğlu, 2021, Shams et al., 2021, Elashmawy et al., 2021)	(Magne and Knezevic, 2009b, Magne et al., 2014, Dartora et al., 2019)	(Aversa et al., 2009, Zarone et al., 2006, Zhu et al., 2017, Chen et al., 2015, Gulec and Ulusoy, 2017, Tribst et al., 2018, Tribst et al., 2021a, Dartora et al., 2021)	(El-Damanhoury et al., 2015, Taha et al., 2018a, Zimmermann et al., 2018, Rocca et al., 2016a, Hasanzade et al., 2020, Ghoul and Salameh, 2020, Hasanzade et al., 2019, Falahchai et al., 2021)

1.2.4 Biomechanical behaviour of endocrowns in comparison to post-core retained crowns and other conventional restorations

Several authors have evaluated the mechanical behaviour of endocrowns compared to other types of restorative procedures, mainly on molars, and few on incisors or premolars. The fracture strength of endocrowns and post constructions on molars was investigated by Biacchi and Basting, where endocrown restorations showed more resistance to compressive forces (Biacchi and Basting, 2012). This agreed with 3D Finite Element studies investigating endocrowns for restoring ET molars (Helal and Wang, 2017, Dejak and Mlotkowski, 2013). However, a recent FEA study reported that endocrowns showed the least tensile stresses in the tooth under axial load, while full-crowns showed less tensile stresses than endocrowns under oblique loads (Tribst et al., 2021a). A study suggested using complete crowns with amalgam core foundations for restoring ET molars with sufficient amount of remaining dentine height (Krance et al., 2018). According to their study, this was shown to provide more recoverable failure modes than endocrown restorations (Krance et al., 2018). On the other hand, a recent study reported higher fracture strength for endocrown restorations compared to inlays and onlays and more favourable failure patterns when compared to inlays for restoring ET molars (Kassis et al., 2020). Another study reported that endocrowns and other build-up restoration designs, were all able to survive far beyond the normal range of masticatory forces (Carvalho et al., 2016).

Restoring anterior ETT by means of endocrown restorations was investigated in some studies (Bankoglu Gungor et al., 2017, Aversa et al., 2009, Ramirez-Sebastia et al., 2014, Zarone et al., 2006, Dejak and Mlotkowski, 2018). The material rigidity of anterior endocrowns and its effect on alveolar bone process was evaluated by a finite element analysis study (Aversa et al., 2009). Bankoğlu Güngör et al. compared the fracture strength and failure modes of endocrowns, zirconia post, and fibre post on anterior ETT (Bankoglu Gungor et al., 2017). The highest fracture strength was reported for endocrowns, which was found to be in agreement with a previous study also investigating anterior teeth (Ramirez-Sebastia et al., 2014). A 3D finite element study also recommended the use of endocrowns in restoring anterior teeth and found that its use presented the advantage of reducing the interfaces of the restorative system (Zarone et al., 2006). However, a recent 3D finite element study revealed that lower contact stresses in the cement-tissue adhesive interface were calculated with conventional post and core crowns in comparison with endocrowns (Dejak and Mlotkowski, 2018). In addition, a recent study concluded that rehabilitation of anterior teeth using glass fibre post retained crowns with ferrule preparation is more favourable than endocrown restorations (Silva-Sousa et al., 2020).

The use of endocrowns in restoring ET premolars remains a controversial issue, especially given that early clinical studies revealed lower survival rates compared to molars (Bindl and Mormann, 1999). Few *in-vitro* studies investigated endocrowns' mechanical behaviour on highly destructed premolars. Some studies found that endocrowns for premolars performed better than the conventional restorations (Chang et al., 2009, Lin et al., 2010), while other studies reported that the efficiency of endocrowns in restoring premolars could be lower than conventional crowns (Forberger and Gohring, 2008). An *in-vitro* study by Forberger et al. did not recommend the use of endocrowns over post-core restorations for mandibular premolars when lithium disilicate crown material was used (Forberger and Gohring, 2008). However, other studies (Rocca et al., 2018, Guo et al., 2016b), showed equivalent results for endocrowns and classical crowns on ET premolars, while the use of flat overlays with only adhesive retention was discouraged (Rocca et al., 2018). Another finite element study suggested the use of endocrowns on premolars but with deeper intra-radicular extensions (Gulec and Ulusoy, 2017). Using numerical and acoustic emission (AE) analysis, two studies investigated the risk of failure for ET premolars with endocrown or conventional crown restorations. They suggested that both restorations for ET premolars with MOD and MODP preparation would present a similar longevity (Lin et al., 2009, Lin et al., 2011).

In conclusion, studies have reported promising results and outcomes for the use of endocrowns in restoring ETT especially for molars, however, the attempt to extend this procedure to anterior and premolar teeth still require more investigations.

1.2.5 Preparation Design

Endocrowns are adhesive restorations that present special biomechanical criteria, and hence require specific preparation designs to satisfy these criteria. Maximum preservation of tooth tissue for bonding rather than extensive preparation for retention, through following a decay-orientated preparation, is the main idea of endocrown restorations (Bindl et al., 2005). Accordingly, its preparation design differs from that of other conventional crown preparations (Pippin et al., 1995).

According to Bindl and Mormmann, a circumferential butt margin with a depth of 1.0-1.2 mm and a central retention cavity inside the pulp chamber with no additional extension into root canals for extra support, are the bases for endocrown preparation (Pissis, 1995, Bindl and Mormann, 1999). The authors suggested preparing for a cylindrical pivot using the following dimensions: a 5 mm diameter and a 5 mm depth for molars and a 3 mm diameter and a 5 mm depth for the first maxillary premolars (Pissis, 1995). However, the exact measurements for the central retention cavity preparation were not clearly determined (Chang et al., 2009). Until now there is no precise or standard design suggested for endocrown preparations; studies have used different preparation designs and some investigated the effect of using different preparation designs on the biomechanical behaviour of endocrowns.

1.2.5.1 Margin Design

Regarding the margin design in endocrown preparation, some authors (Fages and Bennasar, 2013) used a butt margin as described earlier by Bindl and Mormmann (Bindl and Mormann, 1999), while others used a shoulder margin with axial reduction as in all ceramic conventional crowns (Figure 4). Some studies (Taha et al., 2018b, Silva-Sousa et al., 2020) reported statistically significant higher fracture resistance for endocrowns with axial reduction and a shoulder finish line than endocrowns with butt joint design. This was in agreement with a previous study by Einhorn et al. in 2017 (Einhorn et al., 2017). Since butt joint designs are prepared parallel to the occlusal plane, they are expected to resist the compressive stresses by providing a stable surface. They explained that shear stresses can be counteracted through the walls with better load distribution through the walls and margins, this might result when adding short axial walls with shoulder finish line, and hence moderating the load on the pulpal floor (Taha et al., 2018b). In addition, this axial reduction may decrease the thickness of the resin cement in relation to the bulk of ceramic material and thus a decrease in the thermal and polymerisation shrinkage and hence further decrease in the stress transferred to the ceramic restoration (Magne et al., 1999). However, from the stress distribution point of view, endocrowns with flat margin followed by a 90 degrees shoulder were recommended in a 3D finite element study (Guo et al., 2016a). A recent study suggested that using a modified endocrown preparation by adding 2 grooves on the mesial side of the vestibular dentinal wall and on the distal side of the lingual dentinal wall could result in higher fracture strength compared to the conventional butt joint margin preparation (Ghoul et al., 2020). Until now there is no sufficient scientific data regarding the preferred marginal preparation design for endocrowns and more studies are required to assess this topic on different type of teeth.

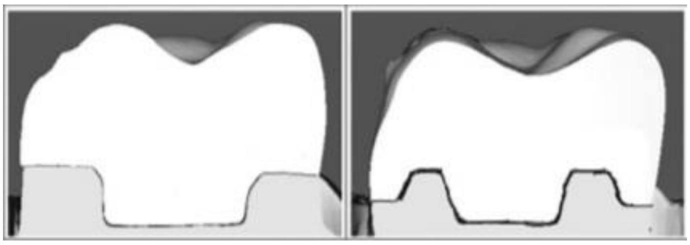


Figure 4 An image presenting endocrown design with A: butt joint margin, and B: shoulder margin preparation. (Einhorn et al., 2017)

1.2.5.2 Endo-core Preparation

The preparation depth of the central retentive cavity, or the length of the endo core is another controversial issue in preparing teeth for endocrowns. Although the length of the intra-radicular portion in post-core retained crowns has been widely debated (Zicari et al., 2012, Büttel et al., 2009, Cecchin et al., 2010) with various results reported, the significance of this endo-core and its length over the *in-vitro* effectiveness of endocrowns has only been investigated by few studies (Hayes et al., 2017, Carvalho et al., 2016, Lise et al., 2017). Further unnecessary preparation of sound tooth structure could be avoided by using a shallow central cavity preparation, and hence reducing the chance of root perforation and excessive tooth weakening. On the other hand, preparing a deeper central retentive cavity could enhance the adhesive retention by providing a greater surface area for retention and might result in better distribution of masticatory forces to the root (Mörmann et al., 1998).

Figure 5 An image presenting endocrowns with different endo-core lengths from shallower to deeper extension in the pulp chamber (left to right), (de Kuijper et al., 2020a).

Clinical and laboratory studies did not use a standard length for endo core preparation. Although suggested by Pissis (Pissis, 1995) that central retentive cavities should be prepared with a depth of 5mm, Bindl and Mormann (Bindl and Mormann, 1999) in their clinical study did not use a standardised depth for endo-core preparation and reported that it ranged from 1 to 4 mm. This could explain the high failure rate in premolars that was caused by loss of adhesion, thus suggesting that insufficient surface available for adhesive bonding might be the reason. However, a later *in-vitro* study failed to find any evidence that the 45° load-to-failure of restored premolars would improve with a deeper retention cavity of 5 mm if only the restoration design factor was considered (Lise et al., 2017). Kanat-Erturk et al. who compared different materials and preparation depth, found that the preparation depth has an effect on the fracture strength only for feldspathic ceramic endocrowns (Kanat-Erturk et al., 2018). Other studies found that endocrown restorations with different endo-core depths presented similar outcomes after extensive fatigue testing (Rocca et al., 2018, de Kuijper et al., 2020a). On the other hand, a finite element study suggested a modified design of endocrowns to be used in two rooted premolars, they recommended extending the central preparation 3mm intraradicularly in both canals in addition to the pulp chamber (Gulec and Ulusoy, 2017). In addition, another finite element study along with an *in-vitro* experiment reported that better mechanical performance was displayed with endocrowns of greater extension inside the pulp chamber of molars (Dartora et al., 2018). Although several studies investigated the influence of the endo core depth on the biomechanical bahaviour of endocrowns, variable results were reported, and until now there is no sufficient scientific data regarding this issue, especially for anteriors and premolars.

Studies also investigated the influence of different endo-core preparation depth on the microleakage and accuracy of the internal fit and marginal adaptation of endocrowns. Rocca et al. found no difference in the percentages of closed margins between endocrowns with 2mm deep endo-cores and 4mm deep endo-cores (Rocca et al., 2018). However, a micro-CT study, showed that endocrowns with 4mm deep endo-cores revealed a larger marginal and internal volume than restorations with 2mm endo-cores (Shin et al., 2017). In this study, cementation did not show significant differences in total discrepancy thickness (Shin et al., 2017). Gaintantzopoulou and El-Damanhoury also reported that an increase in the marginal and internal gaps of endocrowns could be realised when increasing the intraradicular extension of the restorations (Gaintantzopoulou and El-Damanhoury, 2016). However, a recent micro-CT study reported no significant effect when modifying the endocrown’s core depth on the marginal gap in molars (Topkara and Keleş, 2021). Another study reported that different endo-core cavity depths had no correlation with microleakage nor the fracture resistance of endocrown restored premolars (Ghajghouj and Tasar-Faruk, 2019). Interestingly, a recent study reported that the degree of endo-core cavity tapering could affect the marginal and internal adaptation of endocrowns, in which 10 degrees of taper resulted in better adaptation than 5 dgrees (Hajimahmoudi et al., 2021). The previous results suggests that the endo-core depth could affect the fitting accuracy of endocrowns and hence cause other clinical complications, however more studies are required due to the high variability in the results availble to date.

1.2.5.3 Occlusal Thickness

The occlusal thickness of the endocrown restoration and its effect on the mechanical behaviour of the tooth has also been questioned. Usually endocrowns have an occlusal ceramic thickness of 3-7 mm. Tsai et al. reported that an increase in the occlusal thickness of ceramic crowns can increase its fracture resistance (Tsai et al., 1998). Mormann et al. compared the fracture resistance of conventional ceramic crowns with an occlusal thickness of 1.5 mm to the fracture resistance of 5.5 mm thick endocrowns and reported two times higher fracture resistance for endocrowns (Mörmann et al., 1998). Similarly, other *in-vitro* studies reported that ceramic crowns with greater occlusal thickness showed higher fracture resistance (Zarone et al., 2006, Haralur et al., 2020). Some studies recommended maximum preservation of remaining dental tissue in endocrown preparation, since the greater the dental crown remnant, the higher the stress concentration on the restoration (Tribst et al., 2018, Turkistani et al., 2020) (Figure 6).

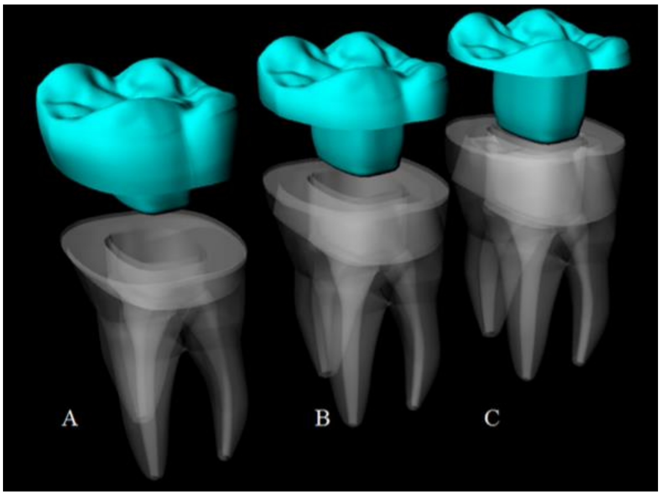


Figure 6 An image illustrating endocrowns with different occlusal thickness in accordance with remaining tooth structure. A: endocrown with 4.5mm occlusal thickness, B: 3mm occlusal thickness, C: 1.5mm occlusal thickness. (Tribst et al., 2018)

Other studies suggested that mechanical strength of bulky restorative designs with high material thickness is not affected by the type of material used (Aktas et al., 2018). They implied that the mechanical strength of bulky restorative designs, like endocrowns are not influenced by the elastic properties of the ceramic. Similarly, Shahrbaf et al. revealed that increased ceramic material thickness by a flat occlusal preparation design does not remarkably benefit from the adhesive support (Shahrbaf et al., 2014). Nevertheless, the selection of a material might be significant in terms of analysing the fracture mode, rather than measuring the fracture load. However, different studies showed controversial results (Magne et al., 2014, Gresnigt et al., 2016b, Magne and Knezevic, 2009b, El-Damanhoury et al., 2015, Shams et al., 2021, Sedrez-Porto et al., 2019).

1.2.6 Cementation

As mentioned earlier, endocrowns mainly depend on the use of proper and reliable adhesion. The quality of the tooth-restoration adhesion is an essential factor to consider when depending mainly on the adhesive approach. When restoring ETT, most of the adhesion interface will be in dentine rather than enamel, and it is reported that the adhesion to dentine is considered weaker than adhesion to enamel (Manuja et al., 2012, De Munck et al., 2012). The immediate dentine sealing (IDS) technique has been proposed as a reliable strategy to increase the bond strength between dentine and indirect restorations (Magne et al., 2005, Gresnigt et al., 2016a). A recent retrospective clinical study that reported a high success rate for endocrowns concluded that if a proper adhesive approach is applied, severely damaged molars and premolars can be effectively restored by endocrowns, even in the presence of massive coronal tissue loss or occlusal risk factors, such as bruxism or unfavourable occlusal relationships (Belleflamme et al., 2017).

Although adhesion quality is an essential factor in endocrown restorations, very few studies have addressed this topic. An *in-vitro* study compared immediate and delayed dentine sealing for luting thick endocrown restorations. They found that immediate dentine sealing does not improve the fracture resistance of endocrown restorations (El-Damanhoury and Gaintantzopoulou, 2016). Another study evaluated the microhardness of light- and dual-polymerisable luting resins polymerised through 7.5mm thick endocrowns. They found that the microhardness of both materials reached at least 80% of the control Vickers microhardness values, which means that both materials can be adequately polymerised when they are used for luting thick endocrown restorations (Gregor et al., 2014). Another study which investigated the minimal irradiation time to reach a sufficient polymerisation of a photopolymerisable restorative bulk-fill resin composite to lute endocrowns, found that a 120-second (40 seconds per buccal, palatal and occlusal site) light-curing of the cement to lute a resin composite CAD-CAM endocrown restoration can be considered sufficient to reach adequate polymerisation (Daher et al., 2020).

A recent study reported that the type of cement system used could significantly affect the microleakage in endocrown restorations (Ghajghouj and Tasar-Faruk, 2019). On the other hand, a study reported that different bonding protocols used for endocrown cementation did not affect fracture strength values (Kassem et al., 2020). More studies are required on this topic in order to reach a proper conclusion and provide clinicians with clear guidance.

1.2.7 Material Selection

The choice of the restorative material and the influence it has on the biomechanical behaviour of ETT restored with endocrowns is an interesting area with very little evidence available to date, especially with the great developments in new materials and digital technologies. The next section will cover this topic, in addition to a background on some materials used today in fabricating endocrowns and indirect restorations.

1.2.7.1 Materials Used in Endocrown Fabrication

As mentioned earlier, the long-term success of ETT to a great extent depends on the selection of an appropriate restorative technique and material, which are able to save the remaining tooth structure and maintain its function (Opdam and Roeters, 2003). Studies have found that the type of materials used in restoring ETT can significantly affect the fracture strength of these teeth and hence affect the outcome of treatment. (Dietschi et al., 2008, Heydecke and Peters, 2002, Rocca et al., 2016b).

Over the last decades, dentistry experienced a shift toward metal-free restorations. To fulfill the ongoing demands of patients and dentists regarding aesthetics, biocompatibility, and long-term survival of the restorations, new types of systems have been introduced, from glass-ceramics to hybrid ceramics and zirconia polycrystal materials (Kelly and Benetti, 2011, Denry and Kelly, 2014). The main goal of the industry is to refine the composition and microstructure of the ceramic materials to develop a stronger ceramic without compromising aesthetics (Gracis et al., 2015). Essentially, a restorative material should meet two main requirements: high mechanical properties and good aesthetics (Stawarczyk et al., 2016, Shahmiri et al., 2018). This has resulted in introduction of various types of dental systems such as feldspathic ceramics, lithium disilicate glass-ceramics, fluorapatite glass-ceramics, monolithic zirconia, polymer infiltrated ceramics and resin-based composites (Takeichi et al., 2013, Layton and Clarke, 2013, Pieger et al., 2014).

In addition to the developments in commercial materials, the introduction of digital dentistry has led to the possibility of a quick and effective chairside production process with CAD/CAM technology. The efficacy of CAD/CAM in dentistry has been proven in both *in-vitro* and *in-vivo* studies (Wittneben et al., 2009). Digital dentistry also increased the demand for monolithic restoration materials (Wittneben et al., 2009). Monolithic crowns are crowns made of the same ceramic material throughout. Bi-layered ceramic crowns have been successfully used in restorative dentistry, however minor chip-offs and restoration failure due to delamination of the veneering material from the framework were often reported (Guess et al., 2008, Sailer et al., 2006, Swain, 2009). In addition, the conventional manufacturing process for different indirect restoration reported some manufacturing imperfections which could eventually cause restoration failure. On the other hand, milling restorations from standardised pre-fabricated blocks using the advanced CAD/CAM technology could lead to a more homogenous structure of the final restoration (Chochlidakis et al., 2016, Gallardo et al., 2018). Moreover, advanced intra-oral scanners used with the digital dentistry technology, have become more accurate, efficient and combined with highly advanced design software (Figure 7). From this context, using CAD/CAM monolithic restorations in restoring ETT seems promising in terms of reducing treatment time and number of visits and also preventing previous reported failures with conventional techniques (Zhang and Kelly, 2017, Wittneben et al., 2009).

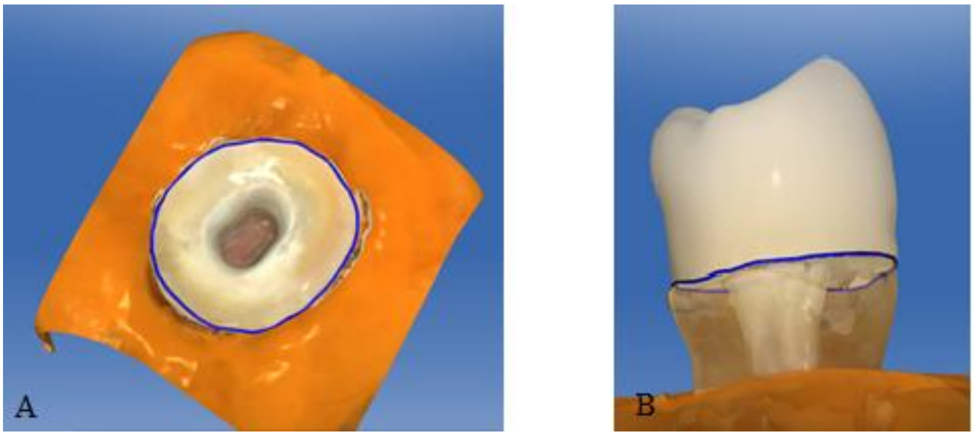


Figure 7 Designing endocrown restorations using CEREC software. A: scanned preparation into CAD model, B: Design for the endocrown restoration.

With the increased range of materials that are currently available to use with the CAD/CAM technology, the decision to choose the right material for different clinical situations has become more challenging. Although endocrowns when first introduced, were described as total porcelain restorations (Pissis, 1995, Bindl and Mormann, 1999), their fabrication is now done by various types of new ceramic and composite materials, thanks to their continuous development along with the increase use of digital technology. Among the newer monolithic CAD/CAM materials used today in the fabrication of indirect restoration are lithium disilicate ceramics, resin based composites and monolithic zirconia.

1.2.7.1.1 Lithium Disilicate (LDS)

This relatively new glass-ceramic material appears to be an attractive and promising material. It has been suggested for monolithic crowns in high load bearing cases due to its combined high strength and good aesthetic properties, hence reducing chipping failures found in conventional layered crowns (Conrad et al., 2007). This material reveals strong needle-like crystals embedded within a glassy matrix (Figure 8) (Ramakrishnaiah et al., 2016, Wang et al., 2015) that resembles the appearance of enamel and can be used for crown fabrications (Gehrt et al., 2013, Pieger et al., 2014). LDS has been reported to have a higher flexural strength (362 MPa) and fracture toughness (2.0 MPa.$m^{1/2}$) (Elsaka and Elnaghy, 2016), than conventional silicate ceramics (Wagner and Chu, 1996). Moreover, a comparable fracture resistance with the gold standard metal-ceramic has been reported (Schultheis et al., 2013).

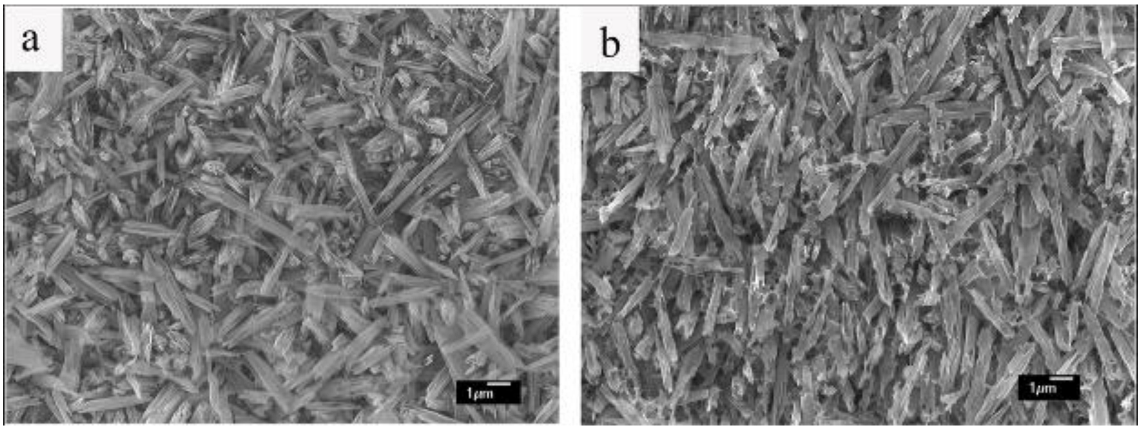


Figure 8 SEM photographs of the etched polished surface of lithium disilicate glass ceramics, illustrating the needle-like crystals microstructure. (a) before heat-pressing, (b) heat-pressed at 950°C, (Wang et al., 2015).

LDS can be monolithic pressed or be milled in CAD/CAM systems. The milled CAD/CAM LDS type is involved in a two-stage crystallisation procedure. According to the manufacturers, it will reach a final flexural strength of about 530 MPa after sintering. Therefore, its flexural strength could reach about 3 to 4 times that of other glass-ceramics (Wendler et al., 2017). There are various commercial types of LDS CAD/CAM blocks available today in the market, with a recent type introduced as a fully crystallised LDS blocks that do not require an extra sintering phase post-milling (LiSi blocks, GC Tokyo Japan). However, there are currently no scientific investigations on such new derivatives.

Lithium disilicate glass-ceramic has been successfully investigated in clinical studies (Gehrt et al., 2013, Fasbinder et al., 2010, Kern et al., 2012). Kern et al. reported an 87.9% survival rate of three-unit LDS crowns after ten years follow-up period (Kern et al., 2012). Gehrt et al. reported a 98.4% survival rate for LDS crowns after eight years follow-up period (Gehrt et al., 2013). Similar promising results were also obtained from laboratory studies (Seydler et al., 2014, Nawafleh et al., 2016, Dhima et al., 2014), which were consistent with the available *in-vivo* results. *In-vitro* studies reported 100% survival rate after 5 years of simulated function (Mitsias et al., 2014), and relatively similar percentages was recorded from *in-vivo* clinical investigations (Pieger et al., 2014, Kern et al., 2012, Gehrt et al., 2013) .

High clinical survival rates for chairside CAD/CAM LDS crowns has also been reported, in which studies showed 100% survival rate after 2 years (Akın et al., 2015, Seydler and Schmitter, 2015), and 83.5% survival rate after 10 years (Rauch et al., 2018). Promising results has also been reported for CAD/CAM monolithic LDS 3 unit fixed partial dentures, in which a 4.7 years survival rate of 93% has been reported (Reich et al., 2014), with limited technical and biological complications. Few clinical and laboratory studies also revealed promising results for CAD/CAM LDS endocrowns (Bindl et al., 2005, Belleflamme et al., 2017). However clinical long-term studies on minimally invasive LDS restorations are still needed.

Generally, the literature has reported high fracture resistance and low material wear for LDS ceramic blocks, supporting their efficiency in producing good aesthetic restorations (Zahran et al., 2008). However, due to the brittleness of glass-ceramics, and their potential abrasive effect on opposing dentition, some concerns and failure cases have been reported for LDS crowns (Sripetchdanond and Leevailoj, 2014, Quinn et al., 2014, Attia et al., 2006). Hence, there is still a demand for enhanced CAD/CAM blocks that are efficient even when used in high load bearing areas for long clinical terms.

1.2.7.1.2 CAD/CAM Composites

New types of chairside CAD/CAM materials that combine the durability and colour stability of ceramics with the improved flexural properties and low abrasiveness of composite resins are now the main focus of many manufacturers (Coldea et al., 2013b, Schlichting et al., 2011). Colour instability, increased material wear, and loss of surface polish were the main concerns with older types of composite resin blocks (Dhawan et al., 2003, Douglas, 2000). In addition, some clinical studies reported an increased failure rate of resin based restorations (Vanoorbeek et al., 2010).

Recently, a novel group of CAD/CAM resin-matrix-ceramics has been introduced. These materials were developed to combine the non-brittle advantageous properties of polymers, with the superior aesthetics of ceramics (Coldea et al., 2013b). The proper classification of this novel material group is still a controversial issue. Resin-matrix-ceramics, hybrid ceramics, and nano-ceramics are all different terms used in the literature (Mainjot et al., 2016). However, these commercial names do not represent the actual chemical composition of these materials (Spitznagel et al., 2018a).

Based on the microstructure and industrial polymerisation method, this new group of materials can be categorised into two subgroups as follows: 1) Resin-based composites (RBC): materials polymerised in high-temperature with a predominately organic phase and dispersed fillers 2) polymer-infiltrated ceramic network (PICN): materials polymerised in high-temperature/high-pressure with a predominately inorganic phase (Coldea et al., 2013b, Mainjot et al., 2016, Spitznagel et al., 2018a).

Several CAD/CAM blocks manufactured from this group of material are available today. Examples of these new block systems include Enamic (ENA; Vita Zahnfabrik), a polymer-infiltrated ceramic, Lava Ultimate Restorative (LVU; 3M ESPE) and Cerasmart (CES; GC Dental Products), as resin-based composites.

The elastic moduli of PICN and resin-based composite blocks were reported to be close to the values of enamel and dentine when compared to LDS blocks which are much harder and stiffer (Alamoush et al., 2018). Another study reported lower fatigue resistance for composite based blocks compared to LDS, however the former was able to survive functional chewing forces (Homaei et al., 2016). A laboratory study showed that high loads of more than 1000 N were required for PICN crowns to fail (El Zhawi et al., 2016). An additional advantage to these blocks is the wear reduction of CAD/CAM burs as claimed by the manufacturers (VITA-Zahnfabrik, 2016). Like LDS, CAD/CAM composite based blocks are also etchable by hydrofluoric acid which creates certain roughness for durable bonding to tooth tissues (Leung et al., 2015).

The combination of these material's edge sharpness, high fracture strength and flexibility makes it possible for them to be used in the fabrication of different types of indirect restorations including endocrowns (Belleflamme et al., 2017, Denry and Kelly, 2014, Homaei et al., 2018, Stawarczyk et al., 2016).

Some clinical studies also revealed the efficiency of CAD/CAM composites in indirect restorations. Chairside fabricated CAD/CAM composite based crowns reported a 96.8% and 92.9% survival rates after two years follow-up when cemented with resin composite cement and resin-modified glass ionomer cement respectively (Chirumamilla et al., 2016). High survival rates were also reported for inlays (97.4%) and partial coverage restorations (95.6%) after a follow-up period of three years (Spitznagel et al., 2018b). Moreover, another study reported a 97% survival rate for CAD/CAM composite onlay restorations after three years (Lu et al., 2018). A 10-year Kaplan-Meier estimated survival rate of (98.8%) was recorded for composite based endocrowns (Belleflamme et al., 2017). However, these clinical studies revealed that CAD/CAM composite based crowns could face cementation or de-bonding complications if the cementation process did not follow the specific recommendations for each applied system. Wear at the restoration surface has also been reported (Chirumamilla et al., 2016, Spitznagel et al., 2018b), therefore, more long-term clinical trials should be monitored.

Although the previously mentioned materials are highly aesthetic, these CAD/CAM glass-ceramic and composite materials are rich in silica and are not as tough as other materials, e.g. materials based on dense zirconia polycrystals; hence, they could be less efficient in high stress bearing cases (Elsaka and Elnaghy, 2016).

1.2.7.1.3 Zirconia

Yttrium oxide-stabilized tetragonal zirconia polycrystal (Y-TZP) material is a biocompatible material that became widely popular in restorative dentistry (Rimondini et al., 2002). Similar to the case in quenched steel (Ban et al., 2010, Noda et al., 2010), zirconia can go through stress-induced transformation toughening mechanism, which gives it excellent mechanical properties. Hence, zirconia is used today in restorative dentistry for fabricating various types of indirect restorations (Ban et al., 2008, Sato et al., 2008). It has the ability to increase in volume when transforming from the tetragonal phase to the monoclinic phase, which will avoid crack propagation and result in higher fracture strength (Manicone et al., 2007). Due to its advanced mechanical features, it has been used as the framework material with fixed partial dentures to replace posterior teeth, with very rare fractures reported in the zirconia framework (Sailer et al., 2007, Edelhoff et al., 2008, Schmitt et al., 2009). On the other hand, chipping of the veneering ceramic was frequently reported (Sailer et al., 2007, Edelhoff et al., 2008, Schmitt et al., 2009). The stability of the system consisting of both the zirconia framework and the veneering ceramic is important from a clinical point of view. Hence, to decrease the costs and at the same time overcome the chipping issue, manufacturers introduced monolithic zirconia restorative material without the veneering ceramic.

The use of monolithic zirconia restorations are becoming more popular nowadays among dentists because of their fabrication simplicity along with their high strength and resistance to fracture (Sulaiman et al., 2016, Sulaiman et al., 2020). A relatively translucent, strong and dense zirconia is used in crown fabrication. Although the framework zirconia used in zirconia-based crowns have a higher flexural strength than monolithic zirconia crowns of equal thicknesses (Matsuzaki et al., 2015), monolithic zirconia crowns has an overall higher fracture resistance than zirconia-based crowns due to increased zirconia thicknesses and lack of veneering ceramics (Sun et al., 2014). However, unfortunately, difficulties in terms of aesthetics are encountered with monolithic zirconia restorations (Kim and Kim, 2019).

Accordingly, some modifications in colour, appearance, and translucency of the monolithic zirconia material have been suggested in an attempt to reach a better aesthetic appearance (Matsuzaki et al., 2015, Harada et al., 2015).

Several modifications in the manufacturing process can be applied to achieve that (Zhang, 2014). For example, reducing crystal size could enhance translucency (Zhang, 2014). In addition, increasing the sintering temperature and yttria content will result in a larger proportion of cubic crystal structure which will also enhance translucency (Zhang, 2014). On the other hand, adding other oxides could change colour and increase opacity (Matsuzaki et al., 2015). Many manufacturers (e.g., InCoris-TZI, Dentsply Sirona; Initial Zirconia Disk, GC Europe; BruxZir-Solid-Zirconia, Glidewell) produced a relatively more translucent zirconia block for fabricating indirect restorations (Zhang and Lawn, 2018). However, gaining translucency without jeopardising the strength of the material is challenging, so the translucency level achieved without losing the mechanical properties of zirconia is limited (Zhang, 2014). Accordingly, this novel group of high-translucent zirconia materials with limited clinical trials should be used with caution until further laboratory and clinical investigations are available due to their low mechanical properties and doubtful aging stability (Zhang, 2014, Muñoz et al., 2017).

CAD/CAM technologies and chairside systems significantly simplified and enabled the production of monolithic zirconia restorations in a single visit. However, unlike previously mentioned materials, zirconia needs a sintering procedure, which takes several hours. The conventional sintering process of Y-TZP zirconia is time consuming, includes a slow heating and cooling rate (typically 5 – 10 °C per minute) in addition to a long dwell time which takes several hours. This produces strong but largely opaque materials. Hence, manufacturers are developing ultra-fast sintering methods for such cases. This led to the introduction of super-speed sintering methods (Ersoy et al., 2015, Kaizer et al., 2017). These methods enabled the production of zirconia crowns in one visit and widened its clinical indications. Hence, monolithic translucent zirconia can now be used as a CAD/CAM chair side material for indirect restorations.

Concerns have been raised about the mechanical effects of speed sintering on monolithic zirconia (Ersoy et al., 2015), however a study reported no significant difference in the flexural strength between speed sintered and conventionally sintered Y-TZP zirconia. Moreover, a much higher flexural strength was reported when super-speed heating, cooling rates, and short dwell time were applied (sample subjected to 1580 °C pre-heated furnace and removed after 10 min dwell time) (Kaizer et al., 2017). Hence it was observed that short sintering time combined with high temperature could enhance the flexural strength of zirconia (Ersoy et al., 2015).

Regarding the adhesive luting of zirconia reconstructions, specific surface pre-treatments are required in order to increase the bonding efficiency and adjust the surface structure. Both chemical and mechanical pre-treatments of the zirconia surface has been reported as critical factors in achieving durable bonding effects (Sailer et al., 2015). Surface abrasion using alumina airborne-particle and the use of an MDP-containing primer resulted in effective bond strength of zirconia restorations with resin cements (Sailer et al., 2015).

Laboratory (Stawarczyk et al., 2013, Janyavula et al., 2013) and clinical research (Lohbauer and Reich, 2017) has shown that lower tooth enamel wear is caused by polished zirconia compared to glazed zirconia, however comparable or less aggressive enamel wear results are reported for glazed zirconia compared to other dental ceramic materials. Accordingly, a well-polished and glazed zirconia surface could eliminate the concerns of wear effects on opposing teeth (Stober et al., 2014). However, intraoral adjustments and alterations to surface characteristics should be considered when evaluating the wear behavior of zirconia restorations. Therefore, proper polishing of zirconia and the opposing antagonists is a prerequisite for an efficient wear resistance (Lawson et al., 2014, Lohbauer and Reich, 2017).

Although very few *in-vivo* studies and clinical evidence is available on monolithic zirconia restorations (Stober et al., 2014, Baixauli-López et al., 2021, Konstantinidis et al., 2018), *in-vitro* studies reported very promising results for monolithic zirconia crowns, with higher fracture loads compared to all other ceramic restorative systems (Zhang et al., 2016). Currently, the scientific clinical data on zirconia fixed partial dentures and monolithic crowns is limited. Preliminary clinical trials revealed that monolithic zirconia seems as a potential treatment option. A recent clinical study showed that monolithic zirconia crowns presented a 5 years survival rate of 98% (Baixauli-López et al., 2021). No cracks, chipping, or fractures within the monolithic zirconia crowns were noticed. Regarding new types of translucent zirconia introduced lately to the market, no clinical trials or evidence on their use are available to date.

Monolithic zirconia was shown to be the most prescribed material for posterior single crowns during a survey conducted in 2015, while lithium disilicate was the most prescribed material for anterior single crowns (Makhija et al., 2016). The results of the previous survey could be due to the high aesthetic properties of lithium disilicate and advanced mechanical strength of zirconia. However, more laboratory and long term clinical studies on the efficiency of monolithic zirconia crowns are needed so that the material's choice is based on strong scientific based evidence rather than personal preferences.

1.2.7.1.4 Conclusion

In conclusion, different materials address different mechanical properties and advantages. All of the above-mentioned materials are available as pre-fabricated blocks for CAD-CAM systems and can be used for fabricating indirect monolithic restorations. LDS ceramics have the advantage of high aesthetic features and enhanced fracture strength, monolithic zirconia were developed to encounter the chipping of veneering ceramics, composite based materials were developed to enable stress absorbance and present an elastic moduli similar to tooth structure. Among this large array of advanced materials, clinicians today have many choices to select the appropriate and favourable material for different cases. However, dentists must consider the biomechanical behaviour of these materials when applied in different clinical indications in order to make a well-informed decision, which requires the need for continuous sound scientific research.

1.2.7.2 Endocrown restorations using different restorative materials

Few studies have investigated the effect of using different types of materials on the mechanical behaviour of endocrowns (Magne and Knezevic, 2009b, Magne et al., 2014, El-Damanhoury et al., 2015, Gresnigt et al., 2016b), however this aspect has been studied thoroughly in ETT restored with post crowns (Loney et al., 1995, Volwiler et al., 1989, Pene et al., 2001, Zhi-Yue and Yu-Xing, 2003, Hu et al., 2003, Schmitter et al., 2006). These studies included specimens with different types of posts. Posts fabricated from high elastic modulus materials, such as metallic ones, have been suggested to enhance the bending resistance of restored teeth by opposing the bending stresses arising from function (Hayashi et al., 2006). However, such posts might be more susceptible to cause catastrophic fractures. Accordingly, posts fabricated from materials with lower elastic modulus such as glass fibre, have been suggested by several authors (Salameh et al., 2007, Tan et al., 2005a, Plotino et al., 2007). The main advantage of glass fibre posts is its ability to enhance the bending resistance, and hence, if failure occurs, it will be more easily restorable. This is because they have a modulus of elasticity close to dentine (Asmussen et al., 1999, Tay and Pashley, 2007). On the contrary, elastic moduli of ceramic, titanium alloys, stainless steel and zirconia are remarkably higher, about five to twelve times higher than natural dentine (Christel et al., 1989, Tay and Pashley, 2007). These inflexible metallic or zirconia posts will cause loading stresses in an unfavourable way, leading to stress concentration in isolated points at the apical level of the root. As a result, un-restorable failures, such as vertical root fracture might occur. This has been confirmed by a considerable number of *in-vitro* (Akkayan and Gülmez, 2002, Newman et al., 2003, Fokkinga et al., 2004, Ausiello et al., 2011, Chuang et al., 2010) and *in-vivo* investigations (Ferrari et al., 2007, Cagidiaco et al., 2008, Schmitter and Hamadi, 2011), as well as by finite element analysis studies (de Miranda Coelho et al., 2009, Eraslan et al., 2009). Nevertheless, opposite results claiming no influence of the post material on the performance of ETT were also reported (Creugers et al., 2005, Naumann et al., 2007, Naumann et al., 2017).

1.2.7.2.1 Mechanical behaviour

In 2009, an investigation by Magne and Knezevic evaluated composites versus ceramics for the fabrication of endocrown molar restorations (Magne and Knezevic, 2009b). They suggested that composite resin materials might increase the fatigue resistance when compared to porcelain. Zarone *et al.* in a 3D finite element study on anterior teeth, also emphasised that materials with mechanical properties close to that of dentine or enamel improve the biomechanical behaviour of the restored tooth, by reducing the areas of high stress concentration such as the restoration-cement-dentine interface (Zarone et al., 2006). Subsequent *in-vitro* studies showed similar results (Magne et al., 2014, El-Damanhoury et al., 2015). However, a later study revealed that under non-axial loading, endocrowns made of composite were more vulnerable (Gresnigt et al., 2016b). In addition, Lise *et al.* (Lise et al., 2017) found that a significantly higher load-to-failure was reported with composite in comparison to lithium disilicate glass-ceramic, but only in the 2.5-mm deep endocrown premolar groups, while in the 5-mm deep endocrown groups, no differences between materials were found. However, for all groups, more than half of the specimens had root fractures, which agrees with a previous study by Forberger and Göhring (Forberger and Gohring, 2008). When the type of CAD/CAM material is the only factor considered, no evidence was found that the choice of material would result in higher load-to-failure (Lise et al., 2017). Similarly, other studies also did not find any significant difference in mechanical behaviour between different endocrown materials (Bankoglu Gungor et al., 2017, Aktas et al., 2018).

On the other hand, a study by Skalskyi et al. recommended that endocrown restorations should be made of high strength materials such as monolithic zirconia, which displayed the highest fracture strength, while the lowest fracture strength out of the materials used was shown for composite resin (Skalskyi et al., 2018). Also another study measuring the stress distribution using different endocrown materials, found that the durability of bonding between the endocrown and the tooth structure may be enhanced with an increase in the elastic modulus of the material; however, it may result in fracture of the residual tooth structure (Zhu et al., 2017). Chen et al. who studied the biomechanical behaviour of endocrown restored molars, found that in comparison to composite resin and Ceramage (a material composed of a PFS (Progressive Fine Structure) filling of more than 73% zirconium silicate ceramic plus an organic polymer matrix), a feldspathic ceramic endocrown transferred less stress, and was more protective to the tooth structure (Chen et al., 2015).

When comparing different types of composite based CAD/CAM blocks together, Taha et al. found that resin nanoceramics showed higher values of fracture than polymer infiltrated ceramics preferring their use for endocrown fabrication (Taha et al., 2018a). However, in a 3D finite element study, Mark II Vitablocs and Vita Enamic were found to be more tooth friendly than Lava Ultimate (Gulec and Ulusoy, 2017).

As a conclusion, previous studies which investigated this issue resulted in variable results, with little evidence that would show the material of higher efficiency. These studies not only varied in their results and conclusions, but also in their protocols set up, type of teeth, materials, and other factors.

Therefore, the type of material best used with endocrowns remains an ongoing research topic and should extend to the newly developed restorative materials.

1.2.7.2.2 Marginal and Internal Fit

In addition to studying the effect of different materials on the mechanical behaviour, another aspect to consider when using different CAD/CAM materials, is the marginal and internal fit accuracy of the endocrown restoration. The clinical long-term success of restorations is influenced by the marginal adaptation and fitting accuracy of these restorations. Studies have shown that marginal gaps might result in microleakage and luting cement dissolution (Jacobs and Windeler, 1991). Wettstein *et al*. reported that an increase in cement gap thickness might lead to a decrease in load to fracture of restorations (Wettstein et al., 2008). Moreover, improper fitting restorations negatively affect the joint bend strength on luting cement and restoration material joint (Molin et al., 1996).

Several factors affecting the final fit or adaptation of restorations have been discussed in previous studies. Some factors reported in the literature include: preparation design, scanning parameters, cement and restorative material type (Ferrari et al., 2003, Hmaidouch et al., 2011, Boitelle et al., 2016, Kosyfaki et al., 2010). Various restorative materials can display different characteristics and physical properties (Tinschert et al., 2000, Mormann et al., 2013), and hence the machinability of these materials using CAD/CAM machines may differ. CAM machinability is an important issue especially for the accuracy of the marginal region. Studies have demonstrated discrepancies in marginal accuracy for different CAD/CAM materials (Mormann et al., 2013). Recent studies have reported that the instrument diameter and milling paths can affect the accuracy of milled restorations (Bosch et al., 2014). It is recommended to optimise CAM procedures and settings for each type of material to achieve the best results for different materials. Each manufacturer provides guidelines on the tooth reduction and minimum thickness of the materials used. For example, a deep chamfer margin of 1 mm, as well as a minimum reduction of 1.5 mm on the occlusal surfaces is recommended by some manufacturers for LD glass ceramic when used in posterior teeth. However, these measurements could be different when different materials are used.

In general, most studies investigating the marginal adaptation and internal fit of restorations used full-contour crowns, inlays or onlays (Mormann et al., 2013, Riccitiello et al., 2018, Ferrari et al., 2003, Revilla-Leon et al., 2018). An endocrown presents a more complex design, with many internal angles that can present a challenge for CAD/CAM milling machines and their specific instrument geometries. Therefore, investigating the fitting accuracy of endocrowns made of different materials is crucial, yet very few studies are available to address this topic.

Zimmermann et al. compared the marginal fit for endocrowns made of three different CAD/CAM materials: (zirconia-reinforced lithium silicate ceramic (Celtra Duo; CD), leucite-reinforced silicate ceramic (Empress CAD; EM) and resin nanoceramic (Lava Ultimate; LU)), showing best marginal fit for resin nanoceramic and worst for occlusal fit of zirconia-reinforced lithium silicate (Zimmermann et al., 2018). This observation agrees with previous studies, revealing that resin-based CAD/CAM restorations present high margin stability (Mormann et al., 2013). Their study suggested that the type of CAD/CAM material used might affect the fitting accuracy of CAD/CAM endocrowns (Zimmermann et al., 2018). On the other hand, significantly higher marginal discrepancies were reported with resin composite endocrowns (Cerasmart, GC, Europe) compared to lithium disilicate counterparts (IPS e.max CAD; Ivoclar Vivadent AG) (El Ghoul et al., 2019b). Such differences between studies can be attributed to differences in specimen preparation, restoration design and fabrication, in addition to the assessment methods applied.

Another study which compared marginal gap values when using different materials in endocrown fabrication, reported that statistically significant increase of the marginal gaps was shown after cementation and thermomechanical aging, however the marginal gap values was not affected by the type of material used (Taha et al., 2018a). A study used blue dye solution to assess the marginal leakage of different endocrown materials. They found that resin nanoceramic showed higher dye penetration than feldspathic porcelain and lithium disilicate (El-Damanhoury et al., 2015). A study by Rocca *et al*. evaluated the marginal adaptation of CAD/CAM composite resin endocrowns and investigated the influence of FRCs reinforcement on it after simulated fatigue loading. They concluded that the marginal adaptation was not significantly affected by the use of FRCs to reinforce the pulp chamber of molars restored with CAD/CAM composite resin restorations (Rocca et al., 2016a).

1.3 Conclusions

In general, until now there is absence of clear information about the clinical, biological and mechanical behaviour of endocrowns and the expectation that this type of restoration would behave similarly or superiorly to conventional crowns. The level of scientific clinical evidence regarding endocrown restorations is considered low, in fact, no RCT investigating single-unit endocrown restorations has been conducted since endocrowns were first described 22 years ago (Bindl and Mormann, 1999). This highlights the need for additional investigations and mainly well-designed clinical studies with long observation periods and RCT's.

Moreover, there is paucity of evidence or clinical guidelines regarding the proper preparation design, material selection, teeth and clinical indications. The reviewed studies were mainly conducted on molars, however, very few investigated anteriors and premolars, with insufficient scientific evidence for these type of teeth. According to the results of the identified *in-vitro* and *in-vivo* studies, and within the limitations of these studies, endocrown restorations have shown promising results especially for molars; however, the attempt to extend this procedure to premolars and anteriors still requires more investigations. In addition, more studies are required to help reach a proper restorative treatment plan, preparation design and material selection.

Chapter 2
Aims, Objectives and Program of Work

2.1 Aims and Objectives:

Endocrowns are being increasingly prescribed to rehabilitate ETT. Although numerous studies have investigated the reliability of post-core retained crowns in restoring such teeth, there is little evidence based on clinical or *in-vitro* studies, which would show the efficiency of endocrowns in restoring ET premolar teeth. The biomechanical behaviour, case selection, preparation design, marginal and internal adaptation, are all essential factors that should be considered carefully when choosing the appropriate restorative technique and material.

The overall aim of this multi-part project is to perform pre-clinical, *in-vitro* testing and computer simulation analysis of the reliability of endocrown restorations in restoring endodontically treated premolar teeth. The clinical significance of this project is to investigate and refine this restorative technique to ensure optimum performance as a conservative alternative to conventional post-core retained crowns used to restore ETT.

To achieve the aims, several *in-vitro* mechanical, radio-graphical, and computational studies will be performed on extracted teeth samples. CAD/CAM restorations using different materials will be used for restoring teeth samples with respect to their clinical applications. This project will have three main objectives that will be presented independently in the form of individual chapters; each with its own introduction, methodology, results and discussion sections, and consequently discussed and correlated to each other in the context of their clinical relevance:

Chapter 3: The effect of thermal and mechanical ageing on mechanical properties of teeth restored with endocrowns using different CAD/CAM materials will be investigated using cyclic and static mechanical testing.

Chapter 4: The marginal and internal fit of endocrowns fabricated from different CAD/CAM substrates will be evaluated using micro-computed tomography imaging technique. The second part of this chapter will examine the association between fitting surface roughness and accuracy of fit.

Chapter 5: The stress distribution and risk of failure of endodontically treated premolars restored with endocrowns presenting various amounts and locations of remaining coronal tooth structure, will be investigated using three-dimensional finite element analysis.

2.2 Program of Work

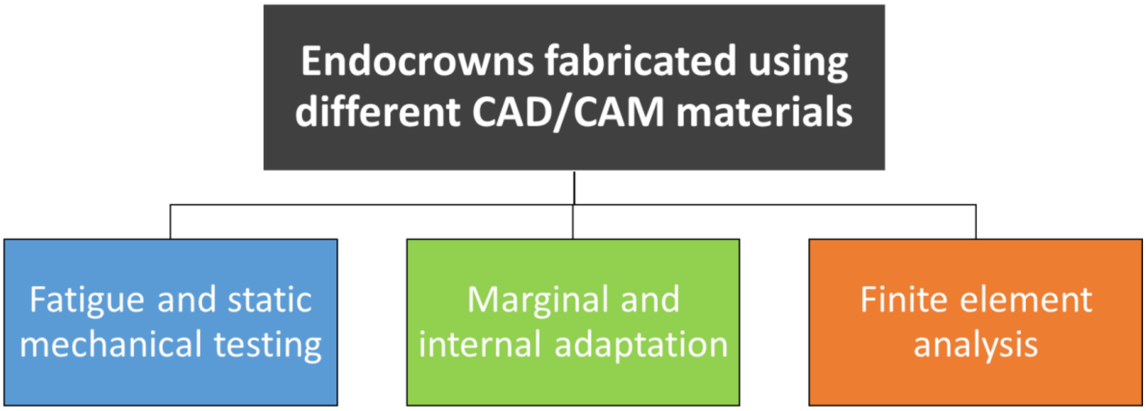


Figure 9 A diagram illustrating the main investigated aspects in the project

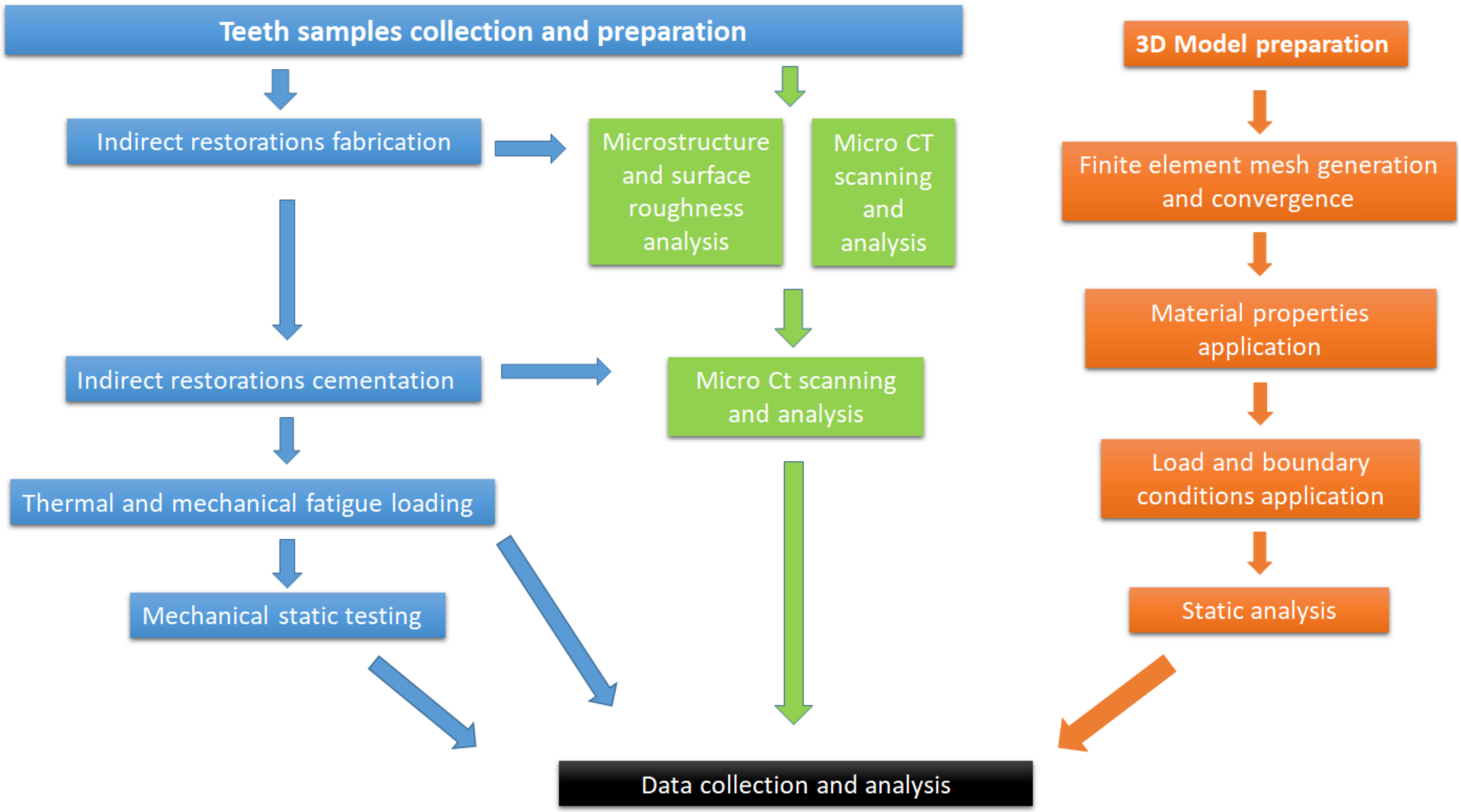


Figure 10 A workflow diagram presenting the main steps carried out in the project from the beginning of sample collection until data analysis. Different colours present the three main experiments conducted, blue: *in-vitro* mechanical study, green: Micro-CT study for fitting accuracy, orange: 3D finite element study.

Chapter 3

Post-fatigue fracture resistance of premolar teeth restored with endocrowns: An *in-vitro* investigation

3.1 Introduction

As mentioned in the previous chapter, the type of restoration technique and material applied are reported to be among the main factors that could affect the treatment success of weakened teeth (Opdam and Roeters, 2003). Adhesive bonding of direct or indirect restorations may negate the need for using posts and thereby avoiding their adverse effects (Rocca and Krejci, 2013). Adhesive restorations demonstrated adequate biomechanical performance *in-vitro* and *in-vivo (Plotino et al., 2008, Angeletaki et al., 2016)*. The type of the restorative material may affect the treatment outcome of weakened teeth owing to the inherent differences in elastic modulus (Signore et al., 2009). Materials with relatively low elastic modulus, similar to dentine, may result in lower stress concentration and less catastrophic failures, while high elastic modulus counterparts may exhibit higher fracture resistance (Chang et al., 2009).

The widespread application of computer assisted design/computer assisted manufacturing (CAD/CAM) has made chair-side fabrication of endocrowns feasible. Additionally, a multitude of materials can be readily utilised for this purpose including ceramic, resin-based composite (RBC) materials, and zirconia (Sedrez-Porto et al., 2020). The outstanding mechanical properties of zirconia dental ceramics and the introduction of translucent zirconia with high aesthetic features resulted in extensive application of this material as a CAD/CAM substrate (Koutayas et al., 2009, Ozkurt-Kayahan, 2016).

Lithium disilicate glass ceramics (LDGC) are also reliable and highly aesthetic CAD/CAM substrates. The traditional LDGC blocks are available in their intermediate metasilicate phase (blue block), in which the material can be milled to form the desired restoration (Saint-Jean, 2014). After milling, the material should be heated in specific conditions to precipitate the final strong lithium disilicate phase. During this stage, the lithium metasilicate crystals fully react with the surrounding glass silica through a solid-state reaction to form small rodlike interlocked crystals of lithium disilicate in a volume fraction of up to 70%, which gives the glass-ceramic its high strength and fracture toughness (Höland et al., 2007, Saint-Jean, 2014). A newly developed lithium disilicate block (GC Dental, Europe) can be milled in its final lithium disilicate phase and does not require extra heating after milling. This is due to the ultrafine structure of this material that was developed by GC's proprietary 'high density micronization' (HDM) technology. This allowed for homogenous dispersion of lithium disilicate micro-crystals within the glassy matrix and hence made it possible to be milled in its final strong lithium disilicate phase.

RBCs are a group of materials with resin polymer matrices highly filled (>50% wt) with inorganic refractory compounds (porcelains, glasses, ceramics and glass-ceramics) (Gracis et al., 2015). Such materials exhibit modulus of elasticity that is close to dentine resulting in lower brittleness compared to ceramics (Mainjot et al., 2016). RBCs require no post-milling sintering or glazing. Polishing yields an optimum surface finish and gloss of RBCs (Mainjot et al., 2016).

With endocrown restorations, the cuspal coverage/protection is achieved by an occlusal onlay-like preparation. The retention of endocrown is obtained primarily from adhesive bonding (Chang et al., 2009, Bindl and Mormann, 1999). A central extension of the endocrown material into the endodontic access cavity increases the area available for bonding and thereby enhances retention (Chang et al., 2009, Bindl and Mormann, 1999). Additionally, the minimally invasive, defect-oriented preparation preserves enamel at the cavosurface margin which in turn, ensures a reliable adhesive bond (Sedrez-Porto et al., 2016). *In-vitro* and Clinical studies reported optimum performance of endocrowns in general, with some concerns regarding their reliability to restore premolar teeth (Govare and Contrepois, 2020, Al-Dabbagh, 2020, Otto and Mormann, 2015).

Premolars are the most commonly teeth involved in biomechanical failure as being subjected to high frequency of non-axial loading during (para)function (Salis et al., 1987). Further, multiple reports indicated suboptimal performance of endocrowns restoring premolars (Otto and Mormann, 2015, Govare and Contrepois, 2020, Al-Dabbagh, 2020). Then, it is prudent to assume that using low elastic modulus RBCs to fabricate endocrowns for premolar teeth may confer a biomechanical advantage. However, there is limited evidence regarding the effect of endocrown material on biomechanical performance. Further, the comparison between endocrown and a gold standard reconstruction, as post-crown, fabricated from a newly developed LDGC material (LiSi Blocks, GC Dental, Europe) is yet to be reported.

3.2 Aim of the study

This *in-vitro* investigation aimed to evaluate the influence of different restorative CAD/CAM substrates on the post-fatigue load-to-failure and failure modes of premolar teeth restored with endocrowns in comparison to post-core retained crowns.

3.3 Null hypotheses

The null hypotheses of this study are:

(i) Load-to-failure and failure modes of fatigued, restored ETT will be similar to control intact teeth.

(ii) Reconstruction design and material type will have no effect on post-fatigue load-to-failure or failure mode.

3.4 Materials and methods

3.4.1 Selection of teeth, endodontic treatment and experimental groups

Seventy sound human mandibular/maxillary premolars extracted from 43 patients as part of orthodontic treatment plan were used in this study following ethical approval (Reference no. D/A 52). Periapical radiographs in bucco-lingual and mesio-distal directions were taken to ensure that all teeth had a single root canal. Teeth were cleaned using an ultrasonic scaler and stored in 1% thymol solution prior to preparation and testing.

Teeth in experimental groups were sectioned 2 mm above the cementoenamel junction (CEJ) using a water-cooled diamond cylindrical bur mounted on a high-speed handpiece. Teeth were endodontically instrumented using a combination of hand K-files and rotary instruments (Protaper® Universal; Dentsply Sirona, Switzerland). Root canal preparation was performed to F5 file and 1 mm short of apical foramina. A solution of sodium hypochlorite (2.5%) was used for irrigation between various files. Following mechanical preparation, sodium hypochlorite (2.5%), EDTA (5%) and distilled water were used for the final rinse. Next, root canals were dried with paper points and obturated using the lateral condensation technique, with gutta-percha (GP) and epoxy resin sealer (AH Plus® sealer; Dentsply Maillefer, Germany). GP cones were seared off at the CEJ point. Canal orifices were then filled with a provisional restorative material (Cavit™; 3M ESPE, USA). All treated teeth were incubated at 37°C and 100% humidity for at least 48 h to allow for complete set of the sealer. Ten randomly selected intact premolar teeth were used as control.

The ETT (n=60) were randomly divided into two groups according to the reconstruction design; endocrowns (C_{endo}) or post-crown (C_{post}). Each group was further divided to 3 subgroups according to the reconstruction material (n=10 p/g) comprising of: (Figure 11)

(i) Cera: RBC material, CERASMART®270 (GC Dental, Europe),

(ii) LiSi: LDGC, Initial® LiSi blocks (GC Dental, Europe), and

(iii) Zir: Monolithic translucent zirconia material, Initial® Zirconia Disks HT (GC Dental, Europe).

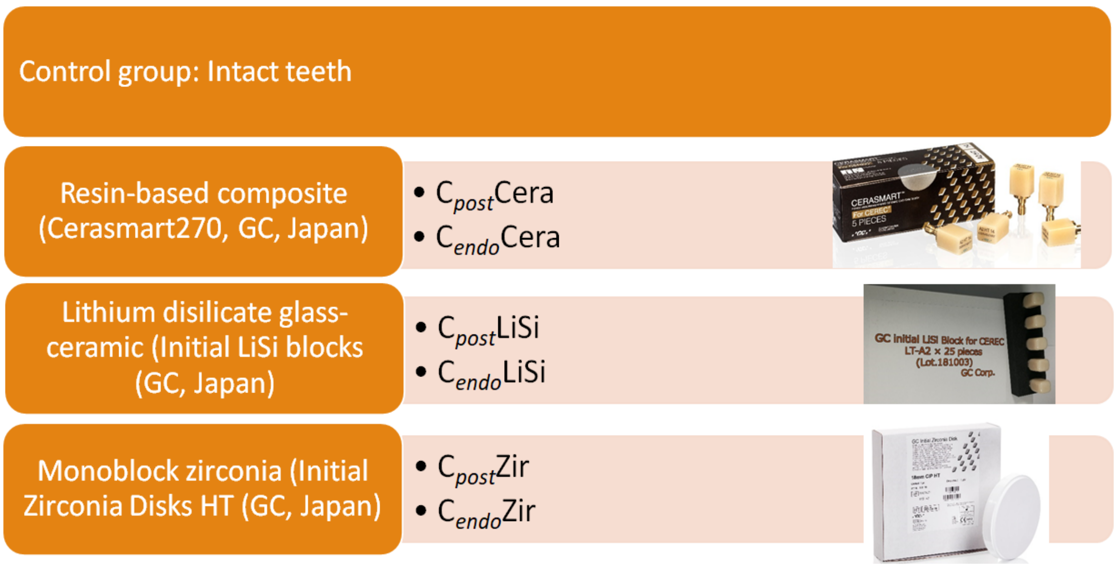


Figure 11 Presentation of the different experimental groups tested in the current study, divided according to the restorative material used and preparation design.

Different materials used in the current study are listed in Table 10.

3.4.2 Tooth preparation for endocrowns (C_{endo})

Tooth preparation was guided by published recommendations (Pissis, 1995). A tapered, round-end, 80-µm grit diamond bur (SBR5 Smooth Cut; GC Dental, Europe) mounted on a high-speed handpiece was used to remove the temporary restoration and prepare a standardised 4 mm-deep, oval, central retention cavity extending into the pulp chamber. A resin-modified glass ionomer liner (Vitrebond®; 3M ESPE, USA) was applied over canal orifice and pulp chamber undercuts. The cavity base and inner surfaces were adjusted with the same diamond bur to obtain homogenous surfaces and to remove areas of stress concentration. All walls had minimum dentine thickness of 1 mm. Next, a 360° butt margin was prepared and smoothed. The preparation was then refined to eliminate undercut areas and achieve an unhindered path of insertion (Figure 12). The amount of tooth tissue reduction was controlled using a periodontal probe.

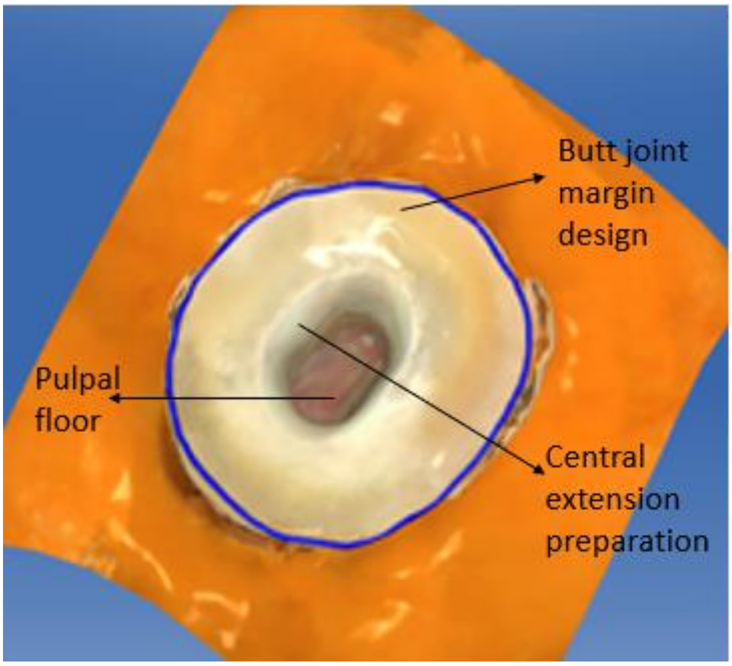


Figure 12 An optical scan for endocrown preparation

3.4.3 Tooth preparation for post-crowns (C_{post})

Initial removal of the GP was accomplished using Gates Glidden drills (Dentsply Maillefer, Switzerland) retaining at least 3-5 mm of GP for apical seal. Post space preparation was refined utilising the drill set provided in the RelyX™ Fibre Post kit (3M ESPE, St. Paul, MN). Glass FRC post (size 2) was placed in the canal, marked and cut at the point where it will be projected 3 mm in the composite resin core build up.

Sodium hypochlorite solution (5.25%) was used to clean root canal before cementation. The post space was rinsed with distilled water and then dried with paper points. Each post was cleaned with ethanol (77%), dried with air and then cemented using a dual-cured cement in conjunction with self-etching adhesive according to manufacturer's instructions (GRADIA™ CORE; GRADIA™ CORE Self-Etching Bond A & B; GC Dental, Europe). Then, a 3 mm-high core was built up with restorative composite resin (Herculite™ XRV; Kerr, Italy) using 1.5 mm increments and light cured for 40 s (Demi Plus; Kerr, USA). Fine diamond finishing burs were used to refine the core build up. Each tooth was prepared with a 2 mm-high, circumferential ferrule and a 1.0 mm-wide rounded shoulder margin at the CEJ.

3.4.4 Fabrication of coronal reconstructions

Prior to de-coronation, the coronal portion of each tooth was scanned using an intraoral scanner (CEREC Omnicam intraoral scanner; Dentsply Sirona). This scan was used to generate a biogeneric copy to fabricate a restoration replicating the original anatomy of the tooth using the CEREC 3D Software (Sirona, Bensheim, Germany).

The CEREC MCXL milling machine (Sirona, Bensheim, Germany) was used to mill Cera and LiSi restorations. Zir restorations were milled from pre-sintered zirconia disks using a 5-axis milling machine (Coritec 250i, imes-icore GmbH). The milled Zir restorations were sintered in a sintering furnace (LHT 01/17D; Nabertherm, Germany) according to the schedule specified by the manufacturer. Cera reconstructions were checked for fit and marginal adaptation then glazed (Optiglaze; GC Dental, Europe) according to manufacturers' instructions. LiSi and Zir reconstructions were polished using a sintered diamond rubber wheel (DiaFlex Fine; DiaShine®, USA).

3.4.5 Luting procedure

Fitting surfaces of LiSi reconstructions were etched using 9% hydrofluoric acid gel for 20 s while Cera and Zir reconstructions were sandblasted (50 μm Al_2O_3, 1.5 bar, 10 mm distance). A 1-Methacryloyloxydecyl Dihydrogen Phosphate (MDP) and silane containing ceramic primer was applied to the fitting surfaces of all reconstructions (G-multi primer; GC Dental, Europe) (Table 10). Light air flow was applied for 5 s to evaporate the ethanol solvent.

Enamel surfaces of prepared teeth were etched with 37% phosphoric acid gel for 30 s and dentine surfaces for 15 s, then rinsed and dried. The adhesive (G-Premio BOND; GC Dental, Europe) was applied using a microbrush, left for 10 s, air dried for 5 s, and then light cured for 10 s. Resin cement (G-CEM LinkForce; GC Dental, Europe) was loaded to the fitting surface of the reconstruction and seated on the prepared tooth with finger pressure. A 1 kg mass was applied to the seated reconstruction in a standardised procedure (Figure 13). Cement excess was removed with a microbrush and each surface was light cured for 40 s. Finally, reconstruction margins were polished using fine diamond points.

Figure 13 A constant weight of 1 kg was applied onto each restoration for 10 minutes until cement polymerisation was complete. The restorations were positioned in a standardised manner using an articulator where 1 kg weight was kept on the upper arm of the device.

Table 10 Commercially available materials used in this investigation.

Material	Type	Manufacturer
CERASMART®270	Resin nano-ceramic CAD/CAM blocks	GC Dental, Europe
Initial® LiSi blocks	Lithium disilicate glass ceramic CAD/CAM blocks	GC Dental, Europe
Initial® Zirconia Disks HT	Monolithic Zirconia discs	GC Dental, Europe
RelyX™ Fibre Post	Glass FRC post	3M ESPE, USA
G-CEM LinkForce	Dual-cure adhesive resin cement	GC Dental, Europe
Herculite™ XRV	Light-cured micro-hybrid composite resin	Kerr, Italy
GRADIA™ CORE	Dual-cured resin cement and core material	GC Dental, Europe
Vitrebond®	Resin-modified glass ionomer liner	3M ESPE, USA
GRADIA™ CORE bond	Two component self-etching adhesive	GC Dental, Europe
G-multi primer	MDP universal primer	GC Dental, Europe
G-Premio BOND	One-component light-cured universal adhesive	GC Dental, Europe

3.4.6 Dynamic fatigue test and thermo-cycling

Restored teeth were incubated at 37°C and 100% humidity for 48 h. Root surfaces were coated with glycerine and embedded in self-cured acrylic resin (Duralay; Reliance Dental Mfg, USA) up to 2 mm below the CEJ. Restored teeth were retrieved and re-embedded in the moulds with light consistency polyether impression material (Impregum™ Soft, 3M ESPE, USA) to simulate the presence of 0.2-0.4 mm-thick periodontal ligament (PDL) (Marchionatti et al., 2014).

A dynamic fatigue testing machine (ElectroPuls E3000, Instron Corp., UK) was used to apply 600,000 loading cycles at a frequency of 5 Hz on all specimens (Figure 14). The effective load range exerted onto the specimens was 10-50 N at 45° angle to the long axis of the tooth using the 250N load cell (with an accuracy level of 0.5% of the reading). The load was applied using a 6 mm-diameter spherical tungsten carbide intender (KVJ A/S, Nykøbing F, Denmark). The test was performed whilst all specimens were immersed in 37℃ distilled water. Upon completion of the dynamic fatigue test, restored teeth were subjected to 1500 thermocycles (5°C and 55°C). Dwell time at each temperature was 30 s, and transfer time was 2 s.

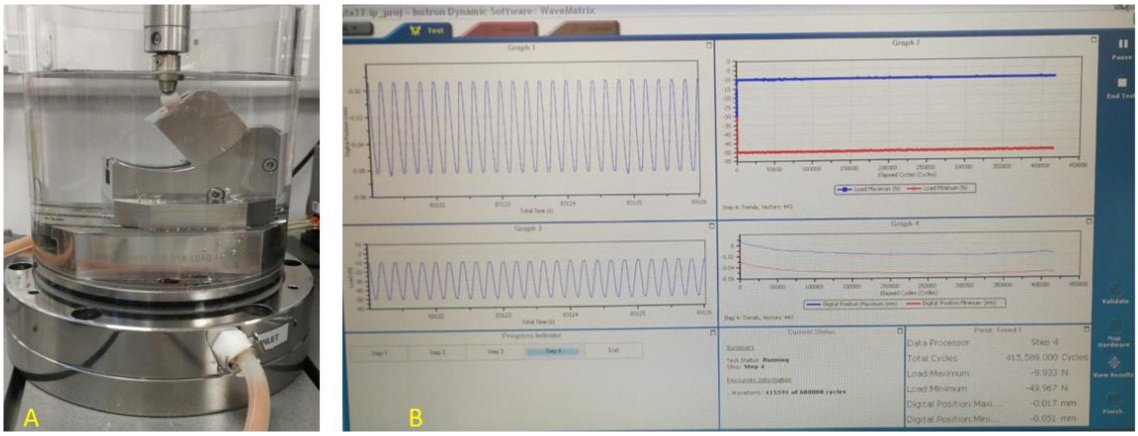


Figure 14 Mechanical compressive cyclic testing of a sample at a load range of 10 to 50N under distilled water, A: sample inserted in Instron Electropuls E3000 (Instron Corp, USA), B: a screen capture for the wavematrix software while test in progress.

3.4.7 Post-fatigue fracture resistance test

Survived samples were re-incubated at 37°C and 100% humidity for 24 hours before proceeding with static testing, in order to standardise the testing environment. A universal testing machine was used to apply a static, compressive load on all specimens (Instron 3365, Instron Corp., UK). Load was applied at 45° angle to the long axis of the tooth with the aforementioned intender contacting the palatal plane of the buccal cusps with a 5KN load cell (with an accuracy level of 0.5% of the reading for readings above 1/100 of the force capacity) and at a crosshead speed of 0.5 mm/min until failure point. The load-to-failure was recorded using Instron Bluehill Software (Instron Corp., UK) (Figure 15). Failure mode was examined for each specimen using an optical microscope (Olympus Optical CO. LTD, Tokyo, Japan) at *x*4 magnifications and categorised into one of the followings (Figure 16):

(i) Type 1: debonding of post, crown, or endocrown without fracture,

(ii) Type 2: fracture of the endocrown or post-crown but not tooth structure,

(iii) Type 3: fracture involving tooth structure above the level of CEJ, or

(iv) Type 4: fracture involving tooth structure at and below the level of CEJ.

Type 1, 2, and 3 failure modes were considered as retrievable failures while type 4 was considered as a catastrophic failure.

Next, fragments that were suitable for fractographic analysis were identified and subjected to fractography. Specimens were ultrasonically cleaned in distilled water for 10 minutes. Dried fractured surfaces were sputter coated with 10 nm layer of gold alloy using a high-resolution sputter coater (Agar scientific, UK). specimens were then subjected to scanning electron microscopy (LEOGemini 1530, Carl Zeiss Microscopy GmbH, Germany) and images of the fracture surfaces were taken at different magnification according to the area of interest (Dartora et al., 2018).

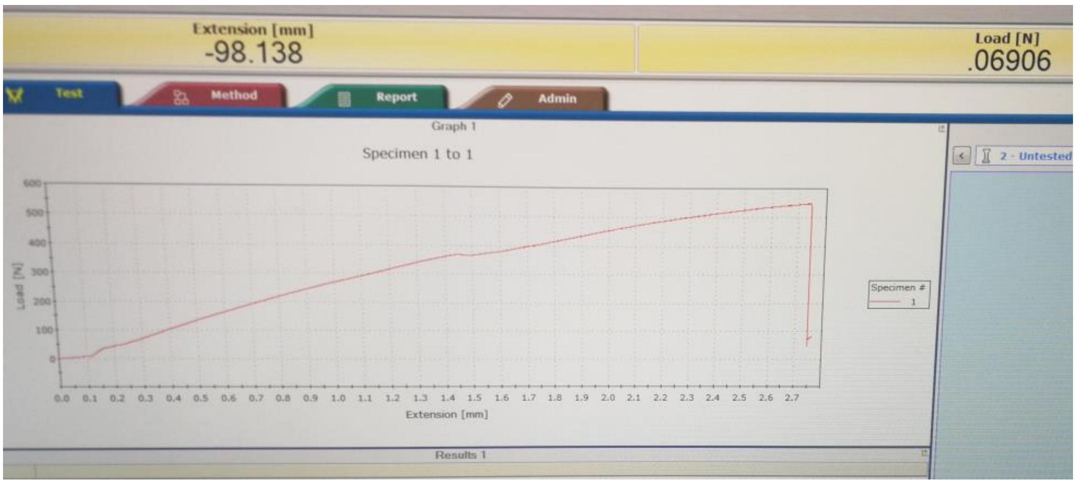


Figure 15 The maximum load at which the specimen fracture was recorded in Newton, Instron Bluehill Software (Instron Corp., UK).

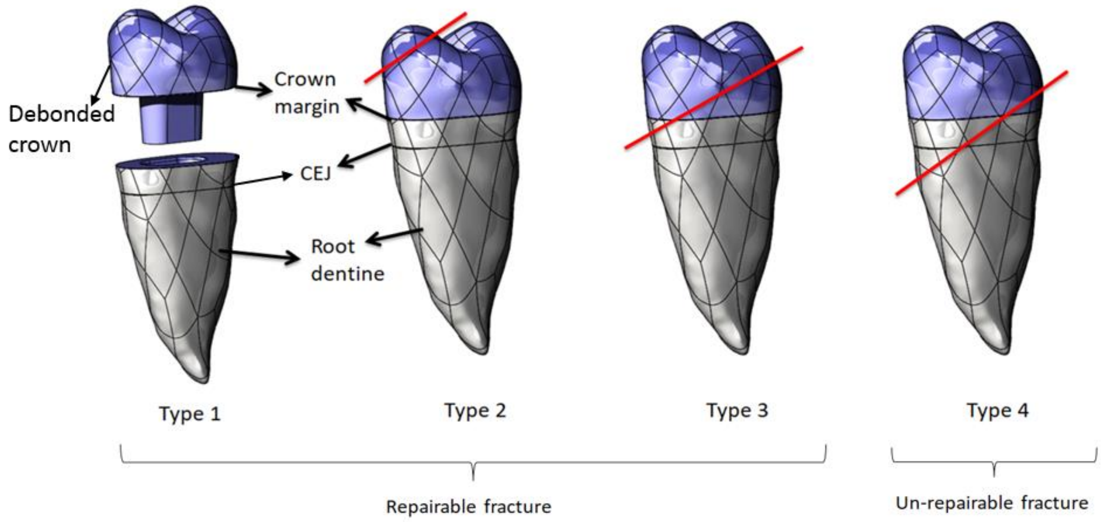


Figure 16 Schematic images illustrating the four modes of fracture presented by the red lines.

3.4.8 Statistical analysis

The load-to-failure data (N) were found normally distributed ($p > 0.05$) using the Shapiro-Wilk test. Data from the load to failure test were submitted to a two-way analysis of variance (two-way ANOVA) for the factors ‘type of restoration’ and ‘type of material’, and *post-hoc* Tukey multiple comparisons at a significance level of $p < 0.05$. Comparisons between experimental groups and control was performed using one-way ANOVA and Tukey HSD post hoc test. Chi-square test was used to compare C_{endo}, and C_{post}, in terms of failure modes regardless the reconstruction material. All analyses were performed using Statistical Package for Social Sciences software (Version 23, IBM® SPSS® Statistics, USA). (Appendix A)

3.5 Results

3.5.1 Cyclic and static testing

All specimens survived the dynamic fatigue test and thermo-cycling without any detectable failure. Two-way ANOVA demonstrated that the reconstruction design ($F=0.33$; $p=0.569$) and material type ($F=2.75$; $p=0.071$) had no significant effect on the load-to failure variable, but the interaction effect was statistically significant ($F=26.83$, $p<0.001$). C_{endo}Cera exhibited a significantly higher load-to-failure compared to C_{endo}LiSi/Zir groups (p≤0.001) but no statistically significant difference was observed between the latter groups (p=0.162). C_{post}Zir exhibited significantly higher load-to-failure compared to C_{post}LiSi/Cera groups (p< 0.001). No significant difference between C_{post}LiSi and C_{post}Cera was detected (p=0.358). The control group of intact teeth demonstrated significantly higher mean post-fatigue load-to-failure when compared with all other experimental groups (p≤0.042) except for C_{post}Zir (p= 0.345).

Failures in Zir reconstructions were primarily catastrophic (p=0.011). No single characteristic failure mode could be determined for the other experimental groups (40–60 % catastrophic failures). Comparing the failure modes between the two reconstruction designs regardless the material type, no significant difference was observed (p=0.573). In cases of root fracture, it was observed that fractures occurred in a mesio-distal direction around the mid sagittal axis in the direction of the applied static load. Only one specimen in C_{endo}Zir group sustained a horizontal root fracture at the level of endocrown pulpal extension. Crown de-bonding was observed once in C_{post}LiSi group (type 1 failure) (Fig. 2). The mean (SD) of post-fatigue load-to-failure values and failure modes of all experimental groups are presented in Table 11 and Figure 17-19.

Table 11 The mean values of post-fatigue load-to-failure (N), standard deviation (SD) and failure modes percentage of all experimental groups. Statistically significant differences (p<0.05) between various materials within the same reconstruction design are indicated by different superscript upper-case letters. Different lower-case letters next to similar materials indicate statistically significant differences between the two reconstruction designs. Different superscript numbers show significant differences between experimental groups and control.

	C_{endo}			C_{post}			Control group
	Cera	LiSi	Zir	Cera	LiSi	Zir	
Load-to-failure: Mean in Newtons, (SD)	758.1 (105.2)^{A,a,1}	547.4 (141.5)^{B,c,1}	460 (112.0)^{B,d,1}	477 (134.4)^{C,b,1}	534.1 (119.1)^{C,c,1}	815.6 (87.6)^{D,e,2}	947.4 (223.0)^{2}
Load-to-failure: Range (N)	569-896	378-835	323-651	304-768	421-802	675-968	560-1227
Type 1 failure	0%	0%	0%	0%	10%	0%	0%
Type 2 failure	0%	10%	0%	10%	10%	0%	0%
Type 3 failure	40%	30%	0%	40%	20%	10%	60%
Type 4 failure	60%	60%	100%	50%	60%	90%	40%

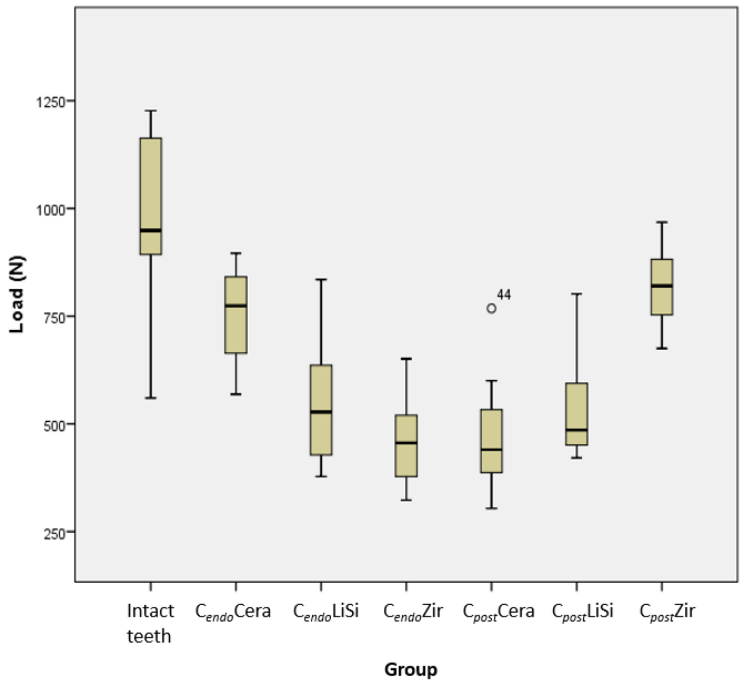


Figure 17 A box-plot diagram presenting the mean values of load to failure (N) and standard deviation (SD) of tested groups.

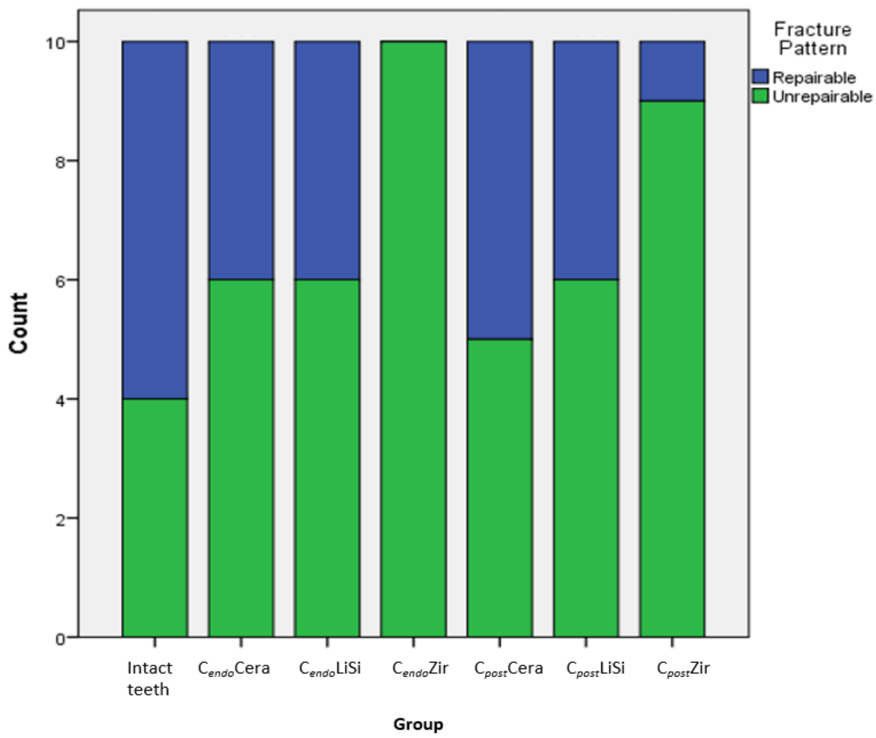


Figure 18 A bar graph presenting the frequency of different fracture modes of the tested specimens in all experimental and control groups.

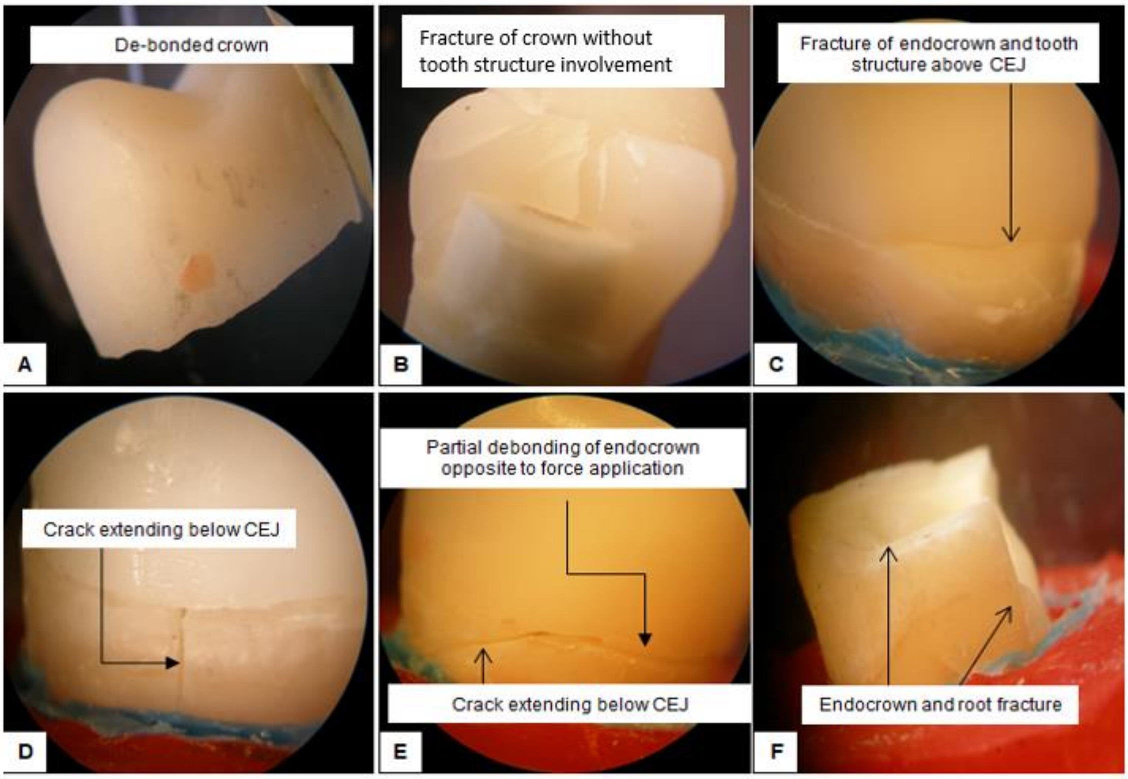


Figure 19 Representative images of various failure modes observed following post-fatigue fracture resistance test. (A) Type I failure: C_{post}Cera, (B) Type II failure: C_{post}LiSi, (C) Type III failure: C_{endo}LiSi, (D&E) Type IV failure: C_{endo}Zir, and (F), Type IV failure: C_{endo}Cera.

3.5.2 SEM analysis:

Only separated or debonded fractured surfaces that were suitable for analysis where further examined under SEM. It was verified that most of these fractured restorations presented separation of the crown in the mesio-distal direction, with or without separation of dental fragments. In general, SEM testing of the fracture surfaces demonstrated that the occlusal surface at the point of loading was the main origin of fractures. The crack origin was usually at the major contact area beneath the loading sphere, in addition some secondary cracks were frequently observed elsewhere at the occlusal surface (Figure 20, Figure 21).

Fracture features detected in the SEM analysis included hackle lines, twist hackles, compression curls and arrest lines. The direction of crack propagation was determined by the direction of hackle lines that were altered with each new compression curl event (Figure 20, Figure 21). Compression curls were observed more often in cera restorations compared to other groups.

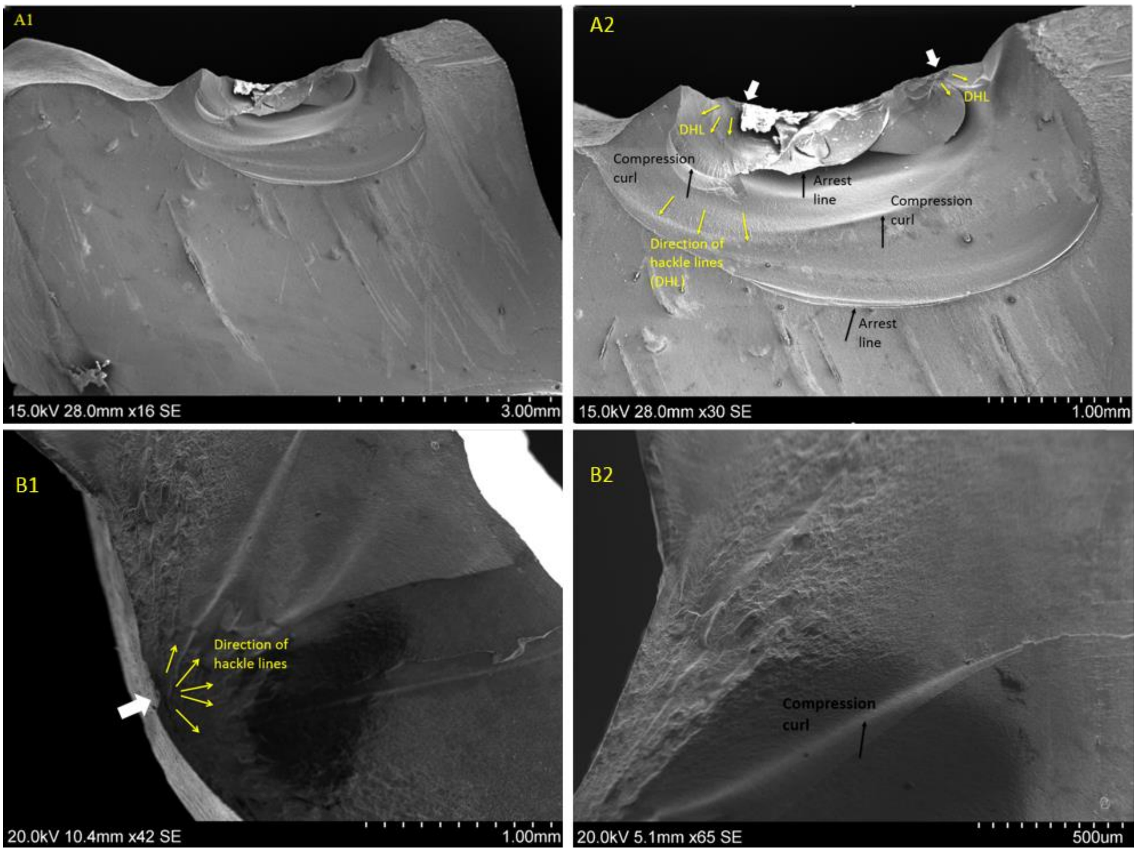


Figure 20 SEM analysis of specimens after artificial ageing and load-to-fracture testing. (A, B) occlusal deformations on Cerasmart endocrown and conventional crown respectively, showing primary and secondary cracks (large arrows) originating at the occlusal surface at and near the point of loading with a corono-apical direction. Additional fracture features like hackle lines (yellow arrows), compression curls and arrest lines are also visible.

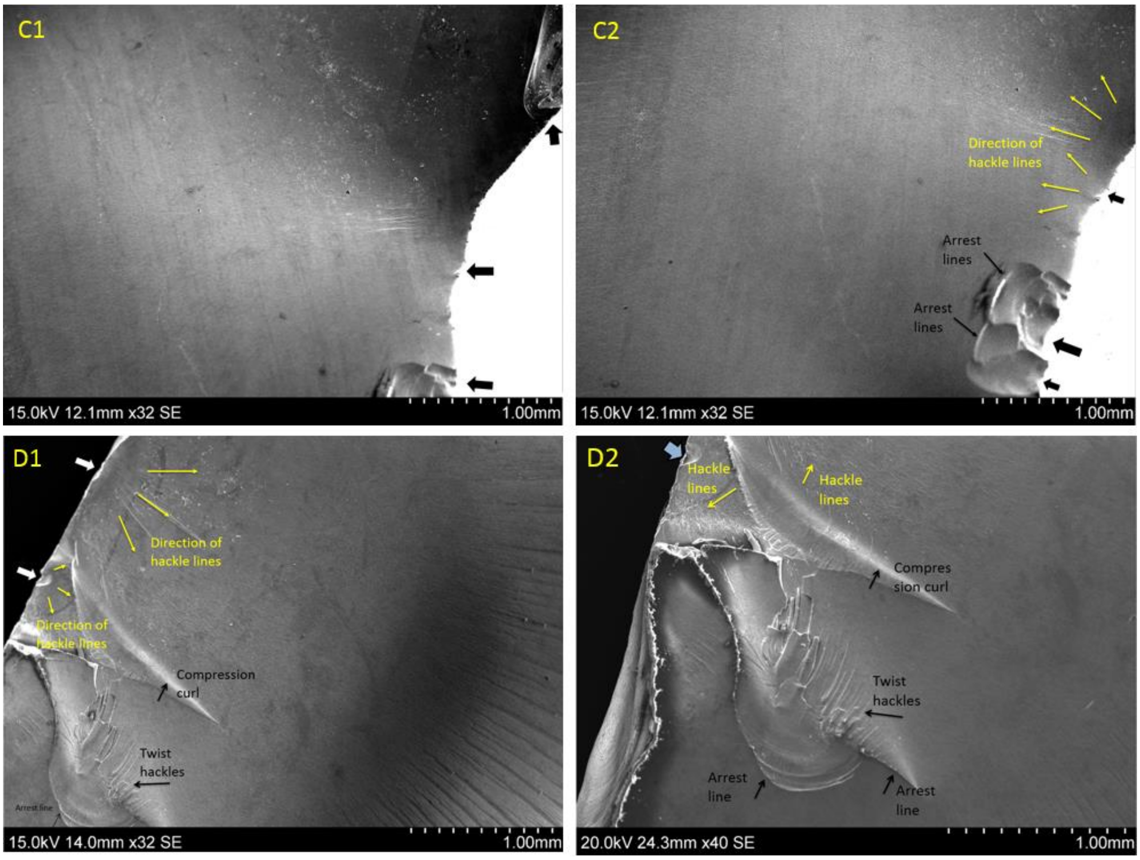


Figure 21 SEM analysis of specimens after artificial ageing and load-to-fracture testing. (C, D) occlusal fractured surface of a LiSi endocrown and conventional crown respectively, showing a smoother fracture surface than Cerasmart restorations (figure 10) with rough deformations only at the point of force application. Primary and secondary cracks (large arrows) originating at the occlusal surface at and near the point of loading with a corono-apical direction. Additional fracture features like hackle lines (yellow arrows), compression curls and arrest lines are also visible.

3.6 Discussion

The purpose of this *in-vitro* study was to investigate the load-to-failure and failure modes of endodontically treated premolars restored with endocrowns or post-crowns fabricated from three contemporary CAD/CAM materials. Intact premolar teeth with comparable root diameter, at the CEJ, and root length were chosen (±10% of mean value). The use of natural teeth for testing might be a source of variability, though it accurately represents the *in-vivo* situation. The use of un-fatigued, sound teeth as control provides a reliable indicator on structural integrity and strength of the used reconstruction design and material. Control teeth demonstrated significantly higher load-to-failure compared to all experimental groups ($p \leq 0.031$) except zirconia post-crowns ($p=0.108$), leading to partial rejection of the first null hypothesis. Our findings agree with another study where both LDGC endocrowns and post-crowns exhibited significantly lower post-fatigue load-to-failure in comparison to intact teeth (Marchionatti et al., 2014). The high load-to-failure of zirconia post-crowns can be attributed to the exceptional strength of zirconia, circumferential 2-mm ferrule, the high tenacity of the glass FRC post and optimum adhesive bonding protocol (Guo et al., 2016b).

A single operator performed all experimental work in order to ensure standardised specimen preparation and testing. Fabrication of all reconstructions using a biogeneric copy may allow extrapolation of clinically relevant findings. Application of 600,000 loading cycles mimics 2.5 years of *in-vivo* function (Kontonasaki et al., 2020). Performing the test in distilled water accounts for the possibility of water-assisted sub-critical crack growth (Ramirez-Sebastia et al., 2013). The latter process is known for its' deleterious effects on the reliability of ceramic materials.

In the current study, a frequency of 5 Hz was applied for the cyclic testing of specimens. The literature showed a variation in the frequency of cyclic loading applied during *in-vitro* testing of restored teeth and ceramic materials. Some studies used low frequencies of (1-3 Hz), (Preis et al., 2013, Senyilmaz et al., 2010, Johansson et al., 2014), while others used higher frequencies (10-20 Hz) (Nicolaisen et al., 2014, Alhasanyah et al., 2013, Zahran et al., 2008). A study by Rosentritt et al has shown that the mean *in-vivo* frequency was 1.2 Hz (Rosentritt et al., 2006). A study tested zirconia restorations under cyclic loading at frequencies 0.1 and 10 Hz, and their results showed significantly greater strength degradation of the tested structures at higher frequencies (Zhang et al., 2004). However, in another study (Rosentritt et al., 2006), loading the all-ceramic structures between 1.6 and 3 Hz had no significant influence on the structure's fracture force. A study (Kelly et al., 1998) used 20 Hz frequency for cyclic loading of leucite-reinforced all ceramic crowns using a staircase approach between 100 to 600 N, with a 100 N step size for 106 cycles in water, and were able to measure fracture loads reasonable for clinical relevance. According to the dental guidelines for cyclic fatigue testing of dental implants

(ISO 14801:2007), testing frequency should be no more than 15 Hz (ISO, 2016).

Light body polyether impression material was used to simulate PDL in this study which reportedly influenced load-to-failure and failure pattern in fracture resistance tests (Soares et al., 2005). This material was particularly chosen as it exhibits a non-linear behaviour when subjected to external stress and elastic modulus similar to PDL (Pini et al., 2002). Application of dynamic and static load at 45° resembles accentuated non-axial loading, replicating worst possible scenario where force is concentrated on the cervical area. All CAD/CAM substrates used in this study were produced by one manufacturer which can potentially limit the generalisability of the findings of this study. Nonetheless, *in-vitro* research studies demonstrated comparable properties/ performance of the used materials when compared to counterparts produced by other manufacturers (Lawson et al., 2016).

In this study, all tested specimens survived the dynamic fatigue and thermocycling. This is an important finding as de-bonding was the primary cause of premolar endocrowns failure in a 5-year clinical study (Bindl et al., 2005). Repetitive stresses during mastication may lead to subcritical crack growth in ceramic materials, thus artificial aging simulation is considered an essential part of *in-vitro* studies (Kelly et al., 2017, Borges et al., 2009), and consequently may result in a lower load-to-failure under compressive testing (Winter et al., 2019, Borges et al., 2009). The repeated chewing forces and the effect of different thermal expansions between cement and tooth or restoration may further affect the marginal and internal adaptation of restorations (Rosentritt et al., 2004). This degradative effect of thermomechanical cycling on dental ceramics has been reported in literature (Blatz et al., 2008, Winter et al., 2019, Kelly et al., 2017, Sieper et al., 2017).

The high biomechanical reliability of the coronal reconstructions in the current study and durable resin adhesive bond may be responsible for the optimum fatigue resistance. Additionally, the adequate tooth structure and restoration preparation/priming, and the use of MDP-based resin cement can also explain the low number (n=1/60) of de-bonded restorations during post-fatigue fracture resistance test (Emsermann et al., 2019, Lawson et al., 2019).

The higher estimates of bite force in the premolar region were reportedly 520 N during function and 800 N during clenching (Bousdras et al., 2006, Hidaka et al., 1999). It is rational to expect a notable increase in such values in ETT owing to the lack of tactile sensory mechanism of the dental pulp (Awawdeh et al., 2017). Only RBC endocrowns and zirconia post-crowns exhibited mean load-to-failure exceeding 750N indicating adequate biomechanical reliability during para-functional activities. Both groups exhibited significantly higher load-to-failure compared to other materials in their respective reconstruction design groups ($p \leq 0.001$) leading to partial rejection of the second null hypothesis. ($p \leq 0.001$) However, when the reconstruction design and type of material independent variables were evaluated individually, both had no significant effect on load-to-failure values ($p = 0.569$, $p = 0.071$, respectively). Interaction effect of reconstruction design and material type was found statistically significant ($p < 0.001$).

A finite element analysis study demonstrated concentration of stresses at the endocrown-tooth structure interface (Zarone et al., 2006). Further, it has been reported that significant mismatch of elastic moduli between tooth structure, reconstruction material and intervening cement layer may predispose for catastrophic failures involving root surface (Zarone et al., 2006). This effect was evident in both reconstruction designs as the highest percentage of catastrophic failures was observed with zirconia reconstructions ($p = 0.011$). The application of an oblique load on stiff zirconia resulted in stress concentration on the facial-cervical area of the root resulting in spall formation involving the CEJ and beyond.

Utilising restoratives with lower elastic modulus may, in theory, improve the biomechanical behaviour of the restorative system. RBCs are composed of polymer-matrices containing predominantly inorganic refractory compounds and exhibit elastic modulus lower than ceramic materials (Gracis et al., 2015). Such materials have a higher tendency to bend under loading and distribute stresses more evenly leading to lower catastrophic failures (Mainjot et al., 2016). Several *in-vitro* studies demonstrated higher fracture strengths and fewer catastrophic failures of RBC endocrowns restoring premolars when compared to LDGC counterparts (El-Damanhoury et al., 2015, Taha et al., 2018a). However, one major concern is the de-bonding of such restorations as a result of stress concentration at the adhesive interface during function.

The RBC CAD/CAM material (CERASMART, GC Dental Europe) used in this study exhibits elastic modulus comparable to dentine (E=9.25 GPa) (Lucsanszky and Ruse, 2019). None of RBC reconstructions de-bonded during dynamic fatigue, thermocycling or fracture strength test, dismissing concerns regarding high risk of adhesive bond failure. Further, C_{endo}Cera demonstrated significantly higher load-to-failure as an endocrown material when compared to LDGC and zirconia ($p \leq 0.001$). The lowest number of catastrophic failures was also observed in RBC reconstructions. Further, C_{post}Cera demonstrated significantly lower load-to-failure compared C_{post}Zr or C_{endo}Cera groups ($p<0.001$). This can be attributed to the difference in strength of Zir and Cera at 1 mm axial thickness (Awada and Nathanson, 2015, Kontonasaki et al., 2020). In C_{post}Cera group, all failures initiated at the cervical-facial aspect of the crown contrary to C_{post}Zr where this area was intact in most fractured specimens. In C_{endo}Cera, the endocrown margin is placed more coronal and the oblique static loading is primarily resisted by natural tooth structure, thus demonstrating higher load-to-failure.

In general, RBCs have improved physical properties, wear resistance and colour stability when compared with direct resin composites owing to the high degree of conversion achieved via post-cure, heat and/or pressure polymerisation (Silva et al., 2017, Awada and Nathanson, 2015). Further, RBCs may outperform ceramic counterparts for the following reasons: (i) reduced time, cost and flaws associated with milling process, (ii) no post-milling firing is required, (iii) ease of adjustment, finishing and polishing with no need to glaze, (iv) less antagonistic tooth wear, and (v) improved repairability and modification using direct composite resin (Silva et al., 2017, Awada and Nathanson, 2015). However, RBCs exhibit lower wear resistance, inferior aesthetic properties, higher water sorption and high plaque retention when compared to ceramics (Silva et al., 2017).

One concern with RBC materials is their high coefficient of thermal expansion. Thermocycling of endocrowns fabricated from Lava™ Ultimate (3M ESPE, USA), a type of RBC, resulted in significantly higher microleakage in comparison to feldspathic and LDGC endocrowns (El-Damanhoury et al., 2015).

Coefficient of thermal expansion is largely affected by the resin content, since resins are the expansile phase of the material. We expect that microleakage can be more significant with CERASMART® as the resin matrix constitutes 29% wt of the material compared to 20% wt of the Lava™ Ultimate (Gracis et al., 2015). Further *in-vitro* and clinical studies are required to elucidate the effects of water storage and thermocycling on the marginal fit of endocrowns fabricated from various types of RBCs.

No significant difference was observed between LiSi endocrowns and post-crowns in terms of load-to-failure and failure modes (p=0.830) which was in agreement with previous studies used LDGC (Guo et al., 2016b, Forberger and Gohring, 2008). However, other studies reported superior reliability of glass ceramic endocrowns compared to post-crowns (Atash et al., 2017, Chang et al., 2009). Different testing methods and parameters may explain such contradictory findings. Further, the LDGC used in this study may differ significantly from previously investigated materials. In the current study, a new LDGC substrate was used. This fully crystallised CAD/CAM block could be an important recent advent in prosthodontics as such materials negate the crystallisation process and may result in better marginal adaptation via elimination of margin distortion observed with post-milling sintering (Kim et al., 2016b, Lise et al., 2017). As per the manufacturer, the milled substrate exhibits very smooth surface finish and requires simple polishing.

Despite the high compatibility between elastic moduli of Cera and dentine, 40% of C_{endo}Cera specimens sustained catastrophic failures. This can be related to the high load-to-failure, which allowed for greater transmission of force to the tooth structure. A similar effect was observed in another study as it has been reported that high fracture strength was associated with catastrophic fracture patterns regardless of the reconstruction design or material (Lise et al., 2017). Further, endocrown margins were placed too close to CEJ, contrary to most clinical situations, which can explain the relatively high number of catastrophic failures. No statistically significant difference could be observed between failure modes among the different reconstruction designs regardless the reconstruction material (p=0.573), leading to partial acceptance of the second null hypothesis.

Regarding SEM analysis for fractured restorations, differences in fracture pattern were observed between the groups. Cera endocrowns showed a fracture pattern with more compression curls compared to other groups, indicating a greater resistance of the material to the applied load and altering the direction of fracture propagation. In LiSi restorations, a more uniform fracture pattern was observed with a smoother fracture surface, which may be associated with the lower value of fracture resistance obtained by the static test.

From a clinical point of view, endocrowns are less time-consuming, cost-effective, contain a single adhesive interface and are associated with minimal risk of iatrogenic damage or technical complications (Bindl et al., 2005, Belleflamme et al., 2017). The supragingival butt margins required for endocrown preparation are easy to prepare and record with conventional or optical impressions. Assessment of the marginal fit, cement excess removal and maintenance of endocrowns are simpler compared to post-crown reconstructions. Recording the details of the apical part of retention cavity can be concerning with intraoral scanners. However, endocrowns with pulpal extension of 2.5 mm or 5 mm could withstand occlusal forces in the premolar region (Lise et al., 2017). Thus, clinicians can prepare shallower retention cavities to avoid such problems. Additionally, the depth scale can be as high as 6.4 mm in some intraoral scanner (Mörmann and Bindl, 2002).

Loss of retention can be a major concern for endocrowns restoring premolar teeth. This can be related to the small surface area available for bonding as well as limited penetration ability of the curing light to polymerise resin cement in the retention cavity. However, the lack of premature failures or de-bonded reconstructions during dynamic fatigue and fracture resistance tests indicating optimum retention of the investigated endocrowns. The current investigation demonstrated that endocrowns may perform as well as post-crowns to restore endodontically treated premolar teeth. Long-term clinical studies are required to substantiate these *in-vitro* findings.

The current study demonstrated some limitations in regards to the limited number of CAD/CAM systems and adhesives investigated. Additionally, other factors like the effect of ferrule preparation and different amount of remaining tooth structure were not evaluated. Therefore, more studies are needed to investigate the effect of these variables on the mechanical behaviour of endocrown restorations.

3.7 Conclusions

Within the limitations of the present *in-vitro* investigation, the following conclusions can be made:

- Post-crown and endocrown reconstructions restoring endodontically treated premolar teeth survived dynamic fatigue test and thermocycling.
- The investigated resin based composite material and monolithic translucent zirconia resulted in highest load-to-failure among endocrown and post-crown reconstructions, respectively.
- Monolithic translucent zirconia resulted in the highest number of catastrophic failures in both reconstruction designs.
- The investigated fully crystallised, lithium disilicate glass ceramic CAD/CAM material demonstrated comparable load-to-failure and similar number of catastrophic failures in both reconstruction designs.

Chapter 4

Evaluation of marginal and internal fit of endocrowns fabricated from different CAD/CAM materials: A micro-computed tomography study

4.1 Introduction

The fitting accuracy of any extra-coronal reconstruction is crucial for long-term clinical success (Felton et al., 1991). Inadequate marginal fit results in premature chemo-mechanical dissolution of the resin cement, discolouration, microleakage, and biological complications such as recurrent caries or periodontal disease (Laurent et al., 2008). Additionally, internal fit may largely influence the reliability of the adhesive interface where cracks are frequently initiated (Zhang et al., 2009, Federlin et al., 2007). A thick cement layer coupled with poor internal fit yields large amount of polymerisation shrinkage stresses leading to premature cohesive or adhesive failures (Ilie et al., 2006, Federlin et al., 2007). This issue is particularly critical in endocrowns given the high ratio of bonded to unbonded surfaces. In contrast, a tight internal fit complicates adhesive bonding and may hinder adequate venting of excess cement leading to incomplete seating and poor marginal adaptation (Boitelle et al., 2014).

Several factors may affect the marginal and internal fit of extra-coronal reconstructions, including margin configuration, preparation design, impression making, reconstruction material, designing tools or software, ceramic material shrinkage compensation, milling process, type of cement (film thickness), and cementation technique and force (Alghazzawi et al., 2012, Piemjai, 2001). Internal misfit values around 25 μm are desirable in order to accommodate resin film thickness in accordance to American Dental Association specifications (materials and devices, 1971). However, an internal discrepancy as large as 150 μm will not adversely affect retention of extra-coronal restorations as reported in several *in-vitro* and clinical studies (Boitelle et al., 2014, Nawafleh et al., 2013).

Full seating of endocrowns can be challenging owing to the configuration of such a reconstruction design. The smoothness of the fitting surface largely influences the ability to seat any reconstruction (Awada and Nathanson, 2015). This can be of particular importance owing to the relatively thick film thickness of the current resin cements and the high risk of generation of positive pressure in the central retention cavity prepared to receive the endocrown (Boitelle et al., 2014). Several factors can influence the finish of the fitting surface of any restoration, including milling procedure and the type and sintering/polymerisation state of the CAD/CAM substrate (Kilicarslan and Ozkan, 2013). Several CAD/CAM materials are utilised for fabrication of endocrowns. Lithium disilicate glass-ceramics and resin-based composites are highly recommended for fabrication of endocrowns for premolar teeth (Belleflamme et al., 2017). However, ceramics with higher modulus of elasticity such as zirconia were associated with higher stress concentration in endocrowns and dentine, which may cause fracture of the residual tooth structure (Hassouneh et al., 2020, Zhu et al., 2017).

Lithium disilicate (LD) glass-ceramics are widely used for the fabrication of extra-coronal restorations owing to their high flexural strength, reliable bond strength to tooth structure and optimum aesthetic and optical properties (Zhang and Kelly, 2017). Both pressed and milled LD glass-ceramic restorations exhibited marginal and internal fit within the clinically acceptable range. However, the pressed restoration demonstrated significantly smaller marginal and internal misfit (Papadiochou and Pissiotis, 2018). The vast majority of machinable LD glass-ceramics are only partially crystallised hence they require post-milling sintering. The latter process may negate the use of this substrate as a chairside ‘one visit’ restoration and may affect the reconstruction’s marginal and internal fit accuracy (Kim et al., 2016b). HDM technology enabled homogenous dispersion of lithium disilicate micro-crystals within the glassy matrix leading to the advent of a fully crystallised, machinable LD glass-ceramic CAD/CAM substrate (Initial® ILS Block: GC, Europe). Such a material allows for reconstructions to be milled to the final size and morphology as post-milling sintering and consequent shrinkage compensation are not required.

Resin-based composite blocks (RCs) are a group of materials with resin polymer matrices highly filled (>50% wt) with inorganic refractory compounds (Zhang and Kelly, 2017). Such materials exhibit a modulus of elasticity that is close to dentine resulting in lower brittleness compared to ceramics. Like fully crystallized LD glass ceramics, RCs require no post-milling sintering or glazing.

RCs exhibit significantly higher material wear when compared to ceramics (Zhang and Kelly, 2017).

The roughness of the fitting surface may affect the accuracy of marginal and internal fit as it may influence reconstruction seating and excess cement venting (Awada and Nathanson, 2015). Partially crystallised glass-ceramics exhibited significantly higher surface roughness compared to RC counterparts (Awada and Nathanson, 2015). The reduced hardness of the lithium metasilicate phase increases the susceptibility for the action of diamond burs used in the milling process. Additionally, the relatively high elastic modulus of the material results in brittle material removal and subsequently more abundant surface flaws (Rippe et al., 2017, Awada and Nathanson, 2015, de Paula Silveira et al., 2017).

The ultrafine, homogenised crystalline lattice within the glassy matrix of the fully crystallised LD glass-ceramics may influence the surface topography of the milled reconstruction. Currently, there is no evidence pertaining to the accuracy of fit of fully crystallised LD glass-ceramics.

4.2 Aim of the study

Accordingly, **this study aimed to** evaluate the marginal and internal fit of endocrowns fabricated from different CAD/CAM materials and the possible association between fitting surface roughness and accuracy of fit.

4.3 Null hypotheses

The null hypotheses for this study were:

I. pre- and post-bonding fit accuracy of endocrowns will not be significantly different, and
II. CAD/CAM material will not have a significant effect on the marginal and internal fit of endocrowns.

4.4 Materials and methods

4.4.1 Specimen preparation

Thirty single rooted premolar teeth of similar dimensions were decoronated 2 mm above the cemento-enamel junction and received endodontic treatment following a standardised protocol (for details please refer to methods and materials section in previous chapter). Next, a standardised endocrown preparation for teeth was done as described by Pissis, 1995 (Pissis, 1995). A tapered, round-end, 80-μm grit diamond bur (SBR5 Smooth Cut, GC) mounted on a high-speed hand-piece was used to prepare a standardised 4 mm-deep, oval, central retention cavity extending in the pulp chamber. A resin-modified glass ionomer liner (Vitrebond®, 3M ESPE, USA) was applied over canal orifice and undercuts. The cavity base and inner surfaces were adjusted with the same diamond bur to obtain homogenous surfaces and to minimise areas of stress concentration. All walls had minimum dentine thickness of 1 mm. Next, a 360° butt margin was prepared and smoothed. The preparation was then refined to eliminate undercut areas and achieve an unhindered path of insertion. The amount of tooth tissue reduction was controlled using a periodontal probe (Figure 22).

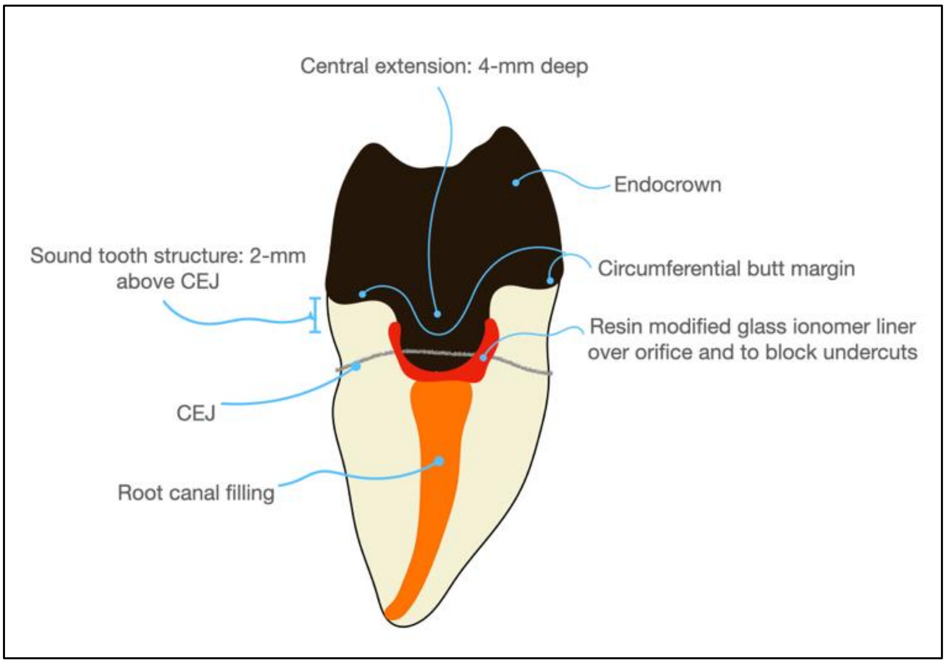


Figure 22 Schematic representation of endocrown preparation features.

An optical impression of the crown of each tooth was taken using an intraoral optical camera (CEREC Omnicam intraoral scanner, Dentsply Sirona) prior to decoronation. This was used as a biogeneric copy to fabricate a restoration replicating the original anatomy of the tooth using the CEREC 3D Software (Sirona, Bensheim, Germany). Biogeneric copy is a crown design technique available with CEREC (Sirona, Bensheim, Germany). This technique is used clinically when you want to copy a pre-existing clinical crown. Pre-operative and post-operative scans are taken in order for the software to stitch together, allowing you to design the restoration.

Teeth were scanned again after preparation (CEREC Omnicam intraoral scanner, Dentsply Sirona) and endocrown design was dictated by the previous biogeneric copy. Cement space was set at 80 μm and endocrowns were milled (CEREC MC XL milling machine: Sirona, Bensheim, Germany) using a similar set of rotary instruments (Step Bur 12 and Cylinder Pointed Bur 12S). A brand new set of burs was used for each group of the following CAD/CAM materials (n=10 p/g):

- CS: a RC material (CERASMART®270: GC Dental, Europe).
- ILS: machinable, fully crystallised lithium disilicate glass-ceramic (Initial® LiSi blocks: GC Dental, Europe)

- EMC: machinable, partially crystallised lithium disilicate glass-ceramic (IPS. e.max® CAD: Ivoclar Vivadent, Schaan).

The EMC endocrowns were subjected to post-milling crystallisation in a ceramic oven (Vita Vacumat 6000m, VITA Zahnfabrik) according to manufacturer instructions.

Fitting surfaces of ILS and EMC endocrowns were etched using 9% hydrofluoric acid gel for 20 s while CS endocrowns were sandblasted (50 µm Al_2O_3, 1.5 bar, 10 mm distance). A 1-Methacryloyloxydecyl Dihydrogen Phosphate (MDP) and silane containing ceramic primer was applied to the fitting surfaces of all reconstructions (G-multi primer: GC Dental, Europe). Light air flow was applied for 5 s to evaporate the ethanol solvent. Enamel surfaces of prepared teeth were etched with 37% phosphoric acid gel for 30 s and dentine surfaces for 15 s, then rinsed and dried. Surface preparation and conditioning prior adhesive bonding is summarised in Table 12.

The adhesive (G-Premio BOND: GC Dental, Europe) was applied using a microbrush, left for 10 s, air dried for 5 s, and then light cured for 10 s. Resin cement (G-CEM LinkForce: GC Dental, Europe) was loaded to the fitting surface of the reconstruction and seated on the prepared tooth with finger pressure. A 1 kg mass was applied to the seated reconstruction in a standardised procedure for 10 minutes. Cement excess was removed with a microbrush and each surface was light cured for 40 s. Finally, reconstruction margins were polished using fine diamond points. All specimens were stored in a laboratory incubator at 37°C and 100% relative humidity for 24 hours.

Table 12 Pre-bonding surface treatment of various substrates

Substrate	Surface treatment
CS*	Sandblasting (50 µm Al_2O_3, 1.5 bar, 10 mm distance 10-MDP**/silane ceramic primer (G-multi primer: GC Dental, Europe)
EMC and ILS*	Etching fitting surface with 9% hydrofluoric acid gel for 20 s 10-MDP**/silane ceramic primer (G-multi primer: GC Dental, Europe)
Enamel	Etching with37% phosphoric acid gel for 30 s Light-cured adhesive (G-Premio BOND: GC Dental,

	Europe)
Dentine	Etching with37% phosphoric acid gel for 15 s Light-cured adhesive (G-Premio BOND: GC Dental, Europe)

4.4.2 Evaluation of marginal and internal fit

The marginal and internal fits were evaluated by means of micro-computed tomography (µCT) (Skyscan 1072, Bruker, Kontich, Belgium). Pre- and post-bonding scans were obtained for each specimen. Pre-bonding scans were performed on endocrowns prior to surface treatment and bonding. At this stage, endocrowns were secured to prepared teeth with a flexible plastic film (Parafilm M; Bemis). Each specimen was stabilised in a scanning tube and positioned perpendicular to the x-ray beam and scanned at 100 kVp, 100 mA, and 9.05 µm pixels, with a 1-mm aluminium-copper filter and an approximate scanning time of 60 min. A reconstruction software program (NRecon; SkyScan) was used to convert the raw data into bitmap (bmp) files.

Data Viewer software (v1.4.3; Bruker microCT) was used for 3D alignment and registration for each scanned specimen. A horizontal cut was made 0.5 mm below the junction between pulpal extension and occlusal portion of the endocrown. This central plane was used to obtain 2 perpendicular cross-sections through the centre of the tooth (x, y axes). Four additional cross-sections were obtained circumferentially at angles equally distributed from each other. This resulted in 6 cross sections with 30° angles apart. Therefore, the number and the orientation of the slices were standardised for all specimens. Due to the unique geometry of endocrowns, this method was adopted to include the central extension of endocrown in all examined cross sections (Figure 23).

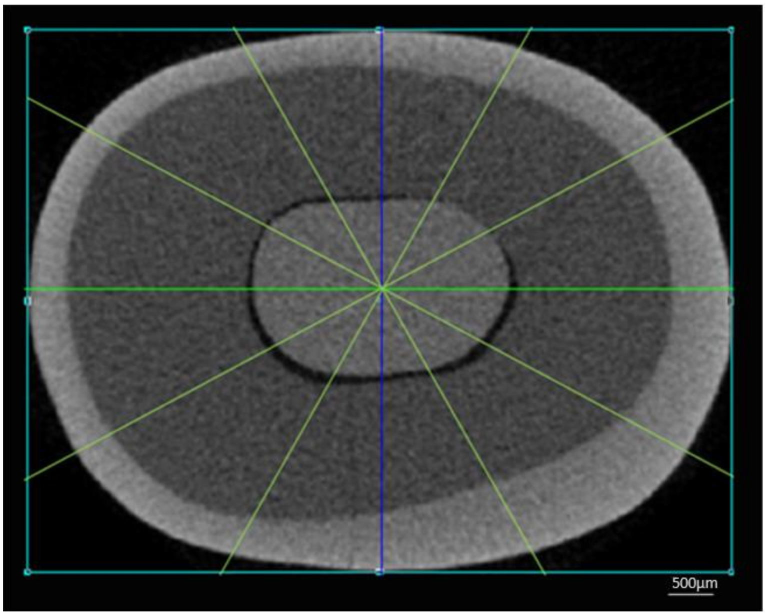


Figure 23 A horizontal cut of CT-scan image presenting the selection of 6 sections through the central of the tooth and positioned at angles equally distributed from each other.

The selection of measurement reference points was based on a description from Holmes et al (Holmes et al., 1989). For the 2D evaluation, each slice was divided into 4 regions of interest (ROI): marginal, cervical, axial, and pulpal. This is done in order to define different regions of crown preparation and analyse areas of higher and lower discrepancies accordingly. Defining areas with higher discrepancies could help understand the potential causes and possible effects.

A total of 16 measurements, 8 mirror-imaged at both proximal sides, were taken on each slice: marginal discrepancy (MD), absolute marginal discrepancy (AMD), cervical misfit (n=2), axial misfit (n=2), and pulpal misfit (n=2) (Figure 24). MD was defined as the perpendicular distance between the intaglio of the endocrown and the tooth preparation. AMD was defined as the distance between the outer point of the endocrown margin and the tooth preparation. The over-extended and under-extended margins for the AMD were both assembled as positive values. The average MD and AMD were defined for measurement of the marginal adaptation (MG), while the average of cervical (C), axial (A) and pulpal (P) misfit were defined for measurement of the internal adaptation. In an attempt to standardise the manual recording of the 2D measurements, all 2D measurements were taken under a computer screen magnification of x400 using the same software (CTan Skyscan; Bruker microCT). In total, 96 points of measurement were evaluated for each specimen (8 measurements on each of the 12 quadrants defined by the 6 slices). The average measurements of the selected points were calculated for each ROI per specimen and then per group.

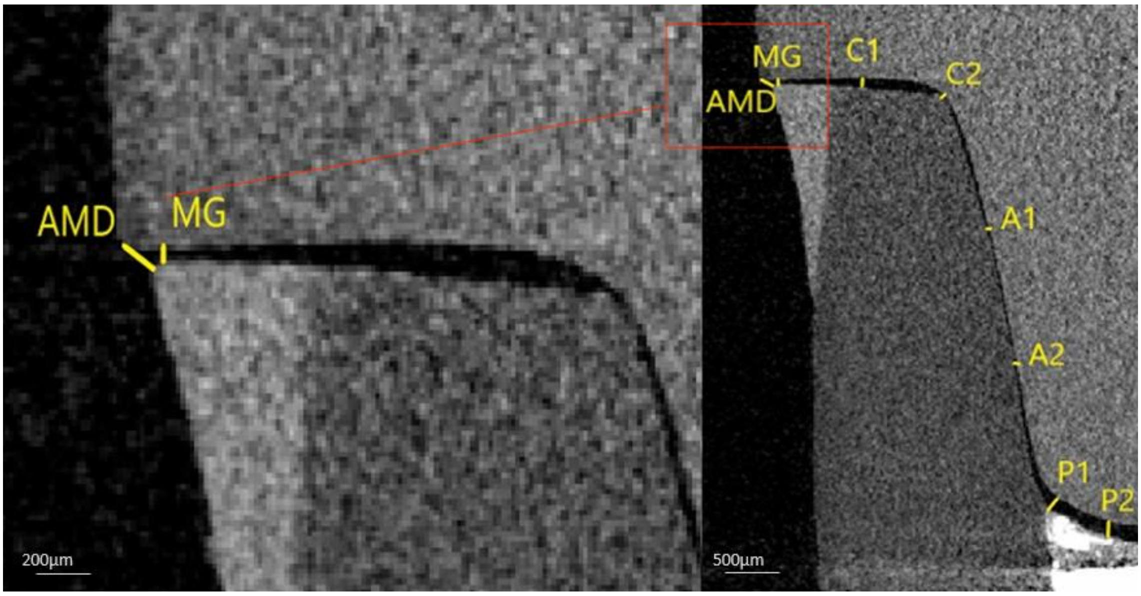


Figure 24 Measurement points for marginal and internal fit in a half cross-sectional cut of CT scan. MG and AMD: marginal discrepancy. C1 and C2: cervical discrepancies. A1 and A2: axial discrepancies. P1 and P2: pulpal discrepancies.

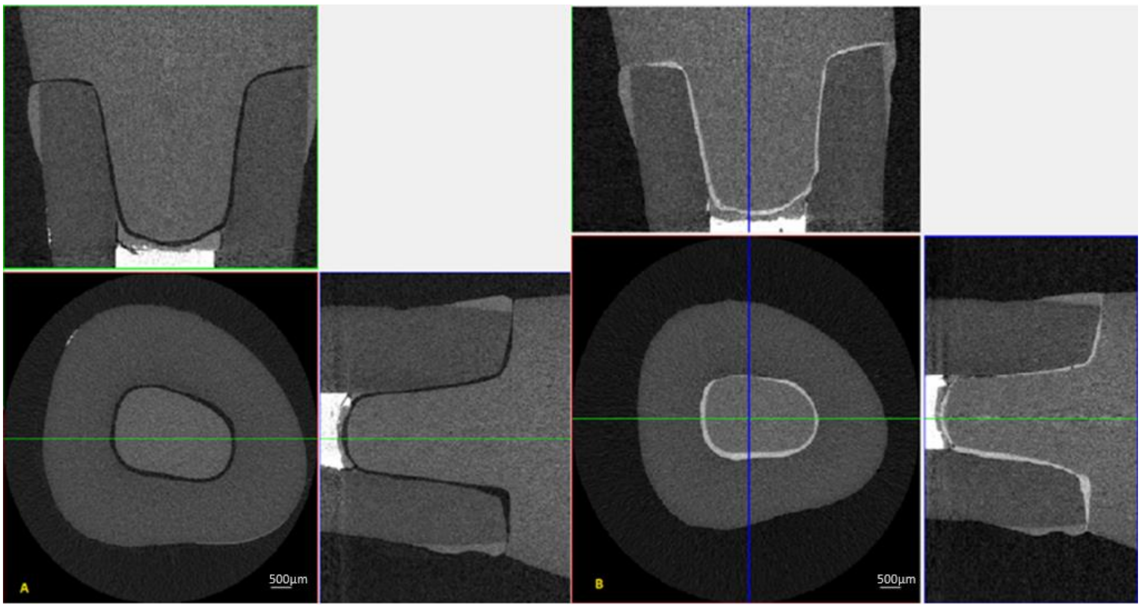


Figure 25 Representative dimensional images before and after cementation. A: uncemented ILS endocrown. B: cemented ILS endocrown. Each image was selected at axial, buccolingual, and mesiodistal section.

Average internal space ratio (AIS) was calculated from a 3D reconstructed scans using CT-analyser software (CTan Skyscan; Bruker microCT). For every transverse slice, a ROI was defined by selecting the area confined between the endocrown and the tooth (cement space). Subsequently, all ROI images were grouped to form the volume of interest (VOI). Since it is not possible to fully standardise natural teeth, a ratio of the total volume divided by the contact surface for the isolated VOI was used to compare between different groups rather than recording only the volume measurement of the VOI. The AIS ratio was calculated by dividing the total volume of the internal space by the contact surface (Figure 26).

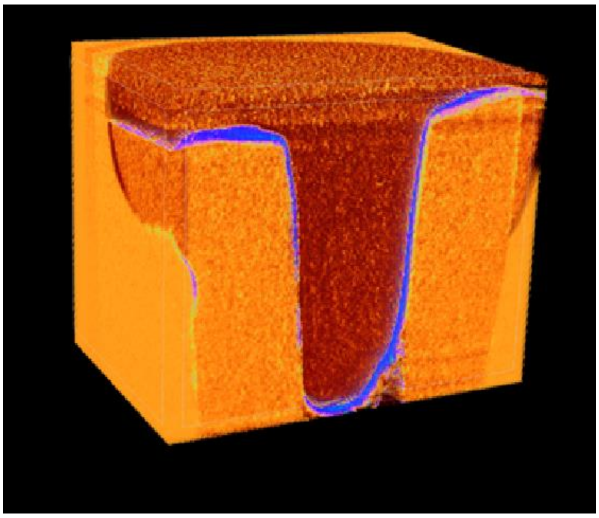


Figure 26. 3D internal fit analysis: A representative 3D reconstructed µCT image of the internal space (blue layer) for a CS endocrown.

4.4.3 Evaluation of surface roughness

Roughness of the fitting surfaces of all endocrowns was characterised using a 3D white light, optical profilometer (NPFLEX, Bruker, UK). Six regions of interest (0.2 mm × 0.2 mm) within the fitting surface of each endocrown were scanned prior any surface treatment. All measurements were made using vertical scanning interferometery mode, scan speed of 1 mm/s. Proscan

Application software (Scantron; Taunton, England) was used to analyse acquired data and apply a Gaussian filter to flatten the acquired images. The arithmetic mean roughness parameter (Ra), mean root square roughness (Rq), maximum profile peak height (Rp), and maximum profile valley depth (Rv) were calculated for the three experimental groups (n=10 p/g).

High resolution field emission scanning electron microscope (SEM) was used to examine surface topography of representative specimens (n=3 p/g) from all experimental groups (LEOGemini 1530, Carl Zeiss Microscopy GmbH, Germany). SEM was operated at 10 kV with a working distance of 20 mm. Fitting surfaces of endocrowns were sputter coated with 10 nm layer of gold alloy using a high-resolution sputter coater (Agar scientific, UK).

4.4.4 Statistical analysis

A Shapiro-Wilk test was used to verify departures from basic normality assumptions. All 2D marginal and internal discrepancy data (μm) were analysed with nonparametric tests. The Kruskal-Wallis test was used to assess differences in misfit values among the 3 experimental groups, upon obtaining significant results, the Mann-Whitney U test was used for *post hoc* analysis. Friedman test followed by Dunn's *post hoc* test for multiple comparisons was carried out to compare different misfit values for particular ROI's in each group separately. Pre- and post-bonding mean misfits were submitted to Wilcoxon test. AIS data were analysed by one-way analysis of variance (ANOVA) and Bonferroni multiple comparisons, (Appendix B). The examined surface roughness parameters (Ra, Rq, Rp, and Rv) were submitted to Kruskal Wallis and Mann Whitney U tests, (Appendix C). Spearman's rank correlation test was used to evaluate correlations between 2D internal misfit and the fitting surface roughness (Ra, Rq). Statistical significance level was set at 0.05 for all tests. All analyses were performed using Statistical Package for Social Sciences software (Version 23, IBM® SPSS® Statistics, USA).

4.5 Results

4.5.1 2D marginal and internal fit analysis

No statistically significant differences were observed in pre- and post-bonding marginal and internal misfit mean values ($p \geq 0.093$). Mean marginal misfit reported (92.4±18 µm) in CS, (77.8±17 µm) in ILS, and (91.3±13 µm) in EMC. The differences between the three groups were not statistically significant ($p \geq 0.096$) (Table 13, Table 14, Table 15 and Figure 27).

Table 13 Pre-bonding mean (SD) values for marginal and internal discrepancy measurements according to ROI for all experimental groups (µm).

	Absolute marginal discrepancy	Marginal discrepancy	Mean (Marginal)	Cervical seat	Cervico-axial angle	Mean (Cervical)	Axial wall	Pulpal angle	Pulpal floor	Mean (Pulpal)
CS	125.5^{a} (33.9)	59.4^{a} (9.5)	92.4^{aA} (18.2)	152^{a} (60.8)	102.2^{a} (31.8)	127.1^{aAB} (42)	124.8^{aAB} (28.7)	157.4^{a} (45.8)	157.2^{a} (36.1)	157.3^{aB} (34.3)
EMC	119.7^{a} (15.1)	63^{a} (15.5)	91.3^{aAB} (13.3)	113.8^{ab} (19.9)	75.4^{a} (12.4)	94.6^{aAB} (11.5)	67.7^{bA} (23.7)	115.3^{b} (10.5)	118.1^{b} (25.8)	116.7^{bB} (15.1)
ILS	104.95^{a} (24.0)	50.7^{a} (12.3)	77.8^{aA} (17.9)	98.1^{b} (22.6)	86.8^{a} (19.2)	92.4^{aAB} (18.4)	77.5^{bA} (25.3)	109^{b} (11.5)	114.4^{b} (9.2)	111.7^{bB} (7.8)

Within each column, similar lowercase superscript letters indicate no statistically significant difference ($p>0.05$).

Within each row, similar uppercase superscript letters indicate no statistically significant difference ($p>0.05$).

Table 14 Pre and post-bonding mean (SD) values for discrepancy measurements according to ROI's of all experimental groups (µm).

Group/ Region	Marginal		Cervical		Axial		Pulpal		Internal	
	Pre-bond	Post-bond	Pre-bond	Post-bond	Pre-bond	Post-bond	Pre-bond	Post-bond	Pre-bond	Post-bond
CS	92.4 (18.2)	105.4 (40.3)	127.1 (42)	144.1 (22.3)	124.8 (28.7)	127.3 (37.4)	157.3 (34.3)	166.9 (22.9)	138.7 (31.4)	149.8 (13.4)
EMC	91.3 (13.3)	89.6 (16.4)	94.6 (11.5)	103.7 (22)	67.7 (23.7)	75.8 (14.4)	116.7 (15.1)	130.6 (26.5)	98 (8.2)	108.9 (20.8)
ILS	77.8 (17.9)	69.1 (10.9)	92.4 (18.4)	92.5 (21.3)	77.5 (25.3)	89.9 (41.3)	111.7 (7.8)	126.4 (23.4)	97.1 (11.2)	105.5 (17.8)

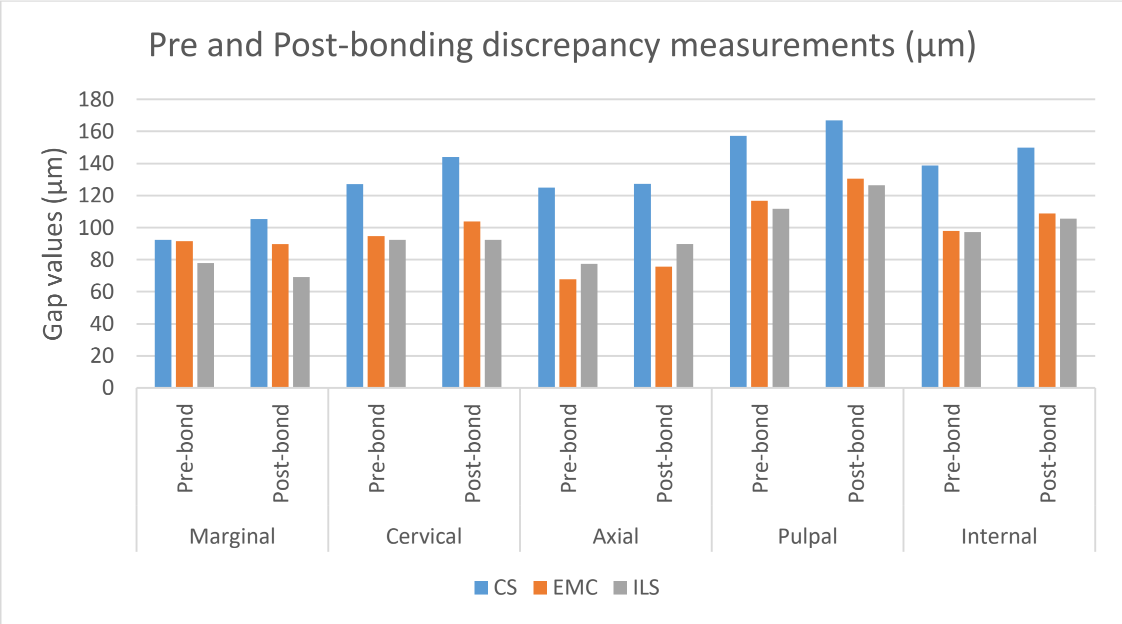


Figure 27 A bar chart presenting the pre and post-bonding discrepancy measurements according to ROI's of different materials (µm).

Table 15 Mean and SD for marginal and internal misfit measurements according to cementation and group in 2D analysis (µm).

	Pre-bonding		Post-bonding	
	Marginal	Internal	Marginal	Internal
CS	92.4^{aA} 18.2	138.7^{aB} 31.4	105.4^{aA} 40.3	149.8^{aB} 13.4
EMC	91.3^{aA} 13.3	98^{bB} 8.2	89.6^{aA} 16.4	108.9^{bB} 20.8
ILS	77.8^{aA} 17.9	97.1^{bB} 11.2	69.1^{bA} 10.9	105.5^{bB} 17.8

Within each column, similar lowercase superscript letters indicate no statistically significant difference (p>0.05).

Within each row, similar uppercase superscript letters indicate no statistically significant difference (p>0.05).

Internal fit varied significantly among all groups ($p=0.001$) where ILS and EMC endocrowns exhibited smaller internal misfit values compared to CS endocrowns. When comparing internal ROI's individually, the cervical region did not show significant difference between groups ($p=0.230$), however in the axial and pulpal regions, CS showed significantly higher misfit values compared to ILS and EMC ($p \leq 0.005$), while no significant difference could be detected between the latter groups ($p=0.165$). Although no significant difference could be found between groups in the cervical region, when looking at the cervical measurement points, ILS showed significantly lower misfit values for the cervical seat measurements compared to CS ($p=0.035$), while no significant difference could be found between the other groups ($p \geq 0.190$) (Table 13).

When the adaptation was compared across all ROI's, the largest misfit was observed at the pulpal and cervical ROIs in all tested groups. The axial and marginal ROIs exhibited the smallest misfit in all groups. In general, internal misfits were larger than marginal counterparts in all groups but only showed significant difference in CS and ILS groups ($p \leq 0.017$) (Table 13 and Table 15).

4.5.2 AIS ratio analysis

ILS group exhibited the lowest pre-bonding AIS (26.1± 3.3 µm) followed by EMC (27.7±4.1 µm) and CS (32.1± 4.0 µm). ILS and EMC groups exhibited significantly lower mean pre-bonding AIS compared to CS ($p \leq 0.037$). However, the difference between the two groups did not reach the statistical significance level ($p=0.711$). Post-bonding AIS ratio measurements were not recorded.

4.5.3 Surface topography analysis

ILS exhibited the least amount of post-milling surface flaws and irregularities. ILS surface was homogenous, shallow parallel, longitudinal, and widely spaced peaks were observed. ILS exhibited the lowest mean Ra, Rq, Rp and Rv mean values (Table 16 , Figure 28 and Figure 29). CS and as-sintered EMC groups exhibited granular surface topography where high, closely packed and pointed peaks were observed (Figure 29).

Table 16 Mean and SD of surface roughness parameters for fitting surface of endocrowns in all experimental groups (μm).

	Ra	Rq	Rp	Rv
CS	1.93[a] (0.37)	2.34[a] (0.41)	3.94[a] (0.79)	4.76[a] (0.84)
EMC	1.77[a] (0.34)	2.02[b] (0.37)	4.36[a] (0.79)	4.24[a] (0.77)
ILS	0.92[b] (0.50)	1.12[c] (0.57)	1.65[b] (0.66)	2.00[b] (1.09)

Within each column, similar lowercase superscript letters indicate no statistically significant difference (p>0.05)

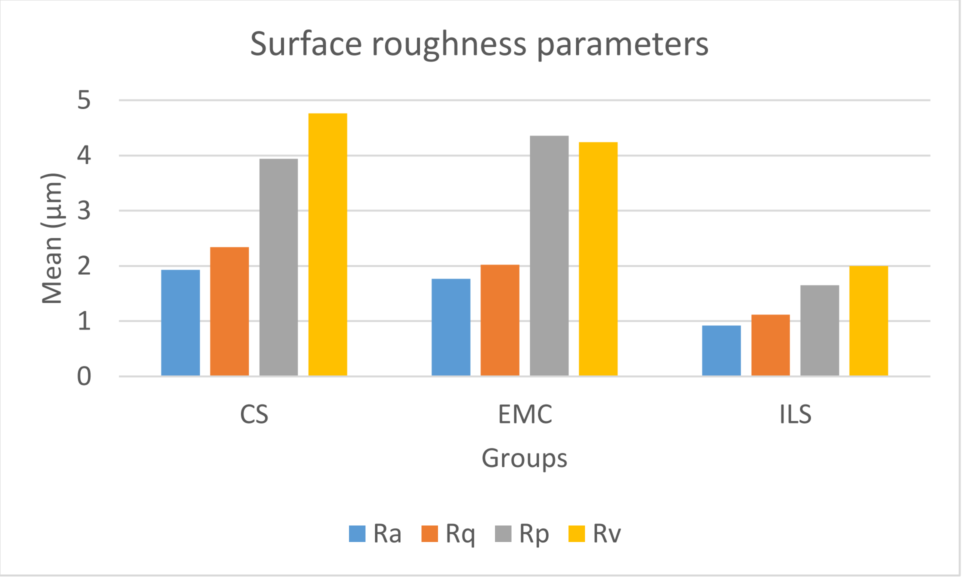


Figure 28: A bar graph presenting the average surface roughness measurements (Ra, Rq, Rp, and Rv) for endocrown's internal surfaces of Groups CS, EMC and ILS.

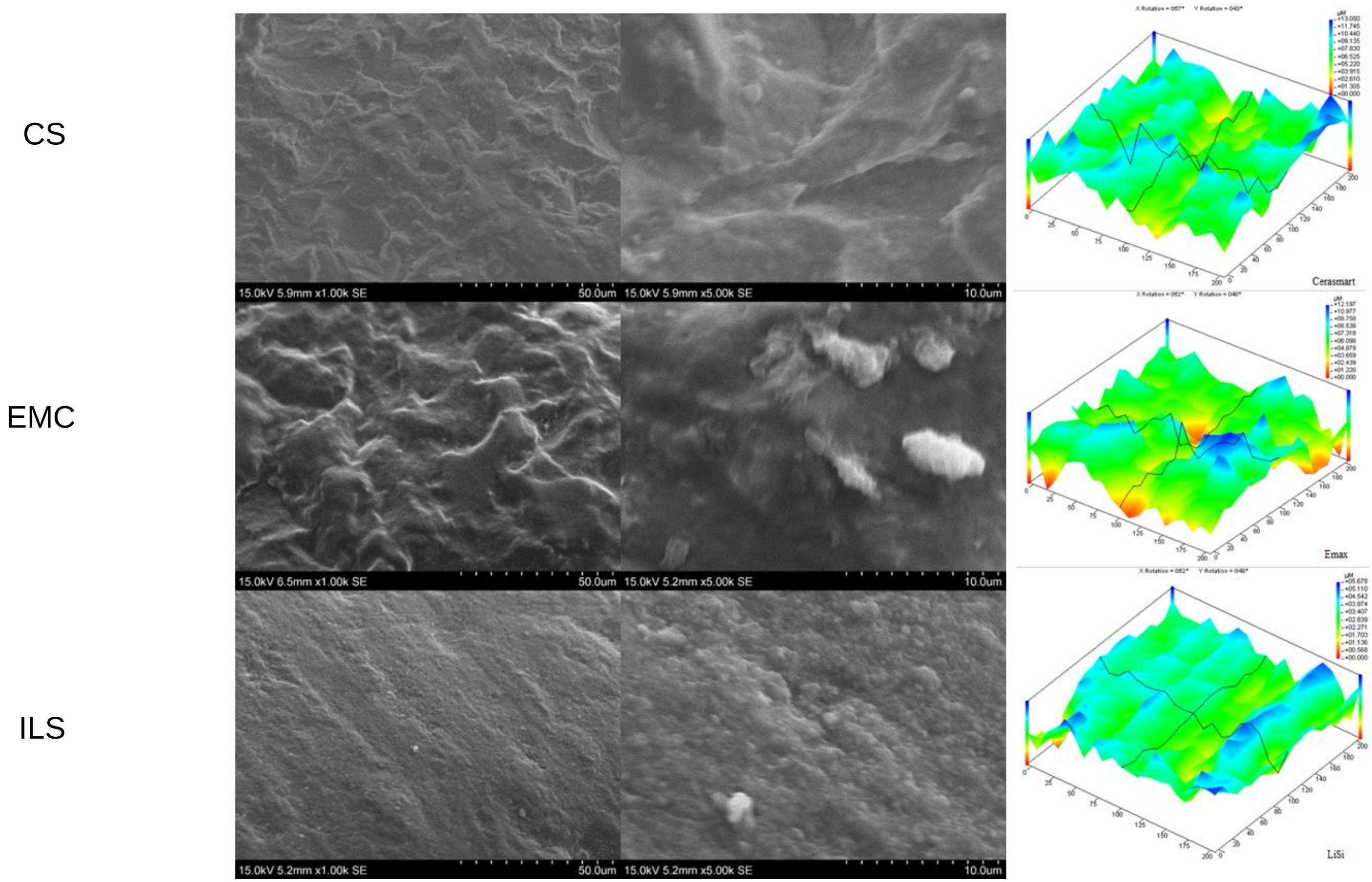


Figure 29 SEM micrographs (left x1K, middle x5K) and profilometry generated height maps (right – 200 × 200 µm) showing the initial surface topography of representative specimens from the three experimental groups.

According to Spearman's rank correlation, no statistically significant correlation was found between the 2D internal misfit and the fitting surface roughness (Ra and Rq) of endocrowns in different experimental groups ($p \geq 0.082$) ($r=0.263$ and 0.322 for Ra and Rq respectively), (Figure 30).

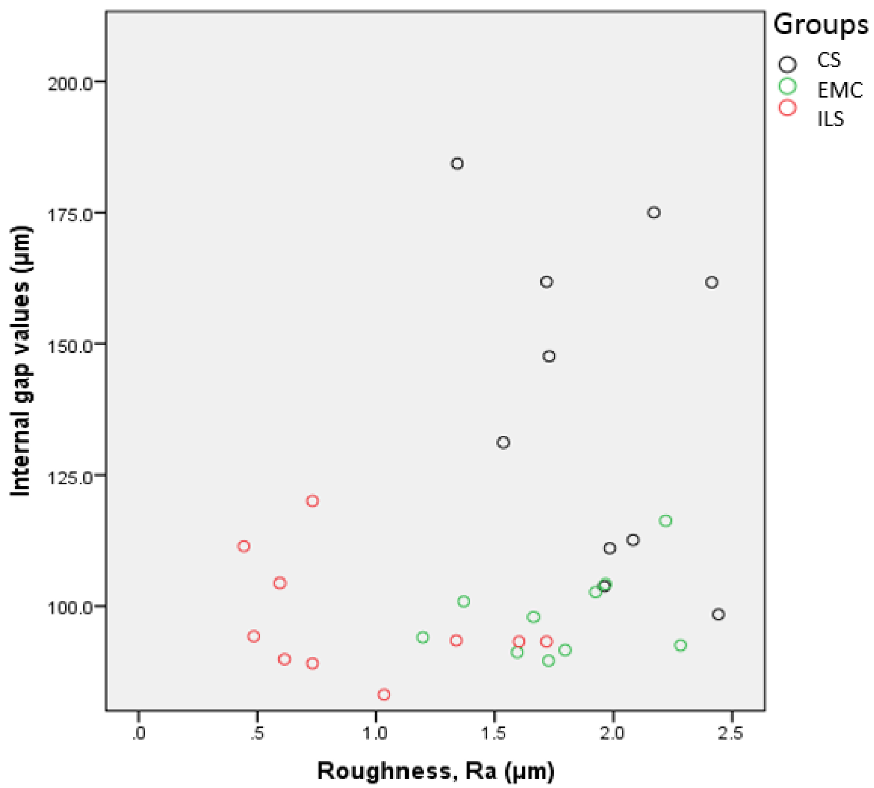


Figure 30 A scatter plot graph showing no correlation between the 2D internal misfit values (µm) and the fitting surface roughness (Ra (µm)) of endocrowns (p = 0.161).

4.6 Discussion

With the intent of investigating the accuracy of fit of endocrowns, µCT was used to determine marginal and internal mis-fits prior and following luting of the reconstructions. Several techniques have been used to evaluate extra-coronal reconstructions' marginal and internal accuracy of fit including: sectioning of embedded specimens (Grenade et al., 2011), replica or weight methods utilising impression materials, profile projectors, and direct measurements with stereo-, light-, or scanning electron- microscopy (Colpani et al., 2013, Nakamura et al., 2003). µCT is a high resolution and non-invasive method for assessment of the accuracy of fit. It allows 2D and 3D visualisation/analysis of the marginal and internal misfits in all planes and different sections. µCT negates the need for sample preparation such as sectioning and reduces the inaccuracies associated with sample alignment in various microscopy techniques. It is highly recommended as a technique for enabling a standardised and reproducible evaluation of the accuracy of fit of extra-coronal reconstructions (Contrepois et al., 2013).

Natural teeth were used in this study despite the associated variabilities owing to the difficulty in standardising specimens, differences in dimensions and physical properties of their hard tissue materials. Nevertheless, as opposed to standardised artificial dies (Moore et al., 1985, Chan et al., 2005), natural teeth accurately resemble the impact of tooth structure preparation for adhesive bonding, such as acid etching on the accuracy of a reconstruction’s fit. Additionally, natural teeth allow reproduction of micro retentive features and their effects on internal fit, and consequences and distribution of polymerisation shrinkage of the resin luting cement. In this study, identical parameters, processes and machines were used in the entire digital workflow from optical scanning to milling of the reconstructions in order to standardise the manufacturing process. Hence, to a large extent, disparities in accuracy of fit can be explained on the basis of different material properties or can be related to post-milling treatments.

The cement space was set at 80 µm for all groups in this study (Dauti et al., 2019). The lack of significant difference between pre- and post-bonding accuracy of fit led to acceptance of the first null hypothesis. Such a finding can be attributed to the very low film thickness of the used resin cement and adhesive system. As per the manufacturer, the thickness of the adhesive and resin cement film thickness is collectively less than 8 µm as a result of the homogenously dispersed barium glass nanofillers within the resin matrix. This was in agreement with a previous study conducted on endocrown reconstructions (Shin et al., 2017), while another study reported a general increase in gap measurements after adhesive bonding (Quintas et al., 2004).

On the other hand, a study by Shin et al 2017 (Shin et al., 2017) reported a significant decrease in the pulp floor misfit following cementation which was attributed to the stresses generated by the resin cement polymerisation shrinkage (Kakaboura et al., 2007) and the loading force applied during cementation. The different cement materials used in these studies, in addition to the different cementation techniques, forces, measurement methods and other factors might contribute to such disparity in the reported findings.

In this study, no statistically significant differences were observed in marginal discrepancy values among all experimental groups leading to partial acceptance of the second null hypothesis. This was in agreement with previous studies, where different materials showed similar marginal discrepancies (de Paula Silveira et al., 2017). However, significantly higher marginal discrepancies were reported with resin composite endocrowns (Cerasmart, GC, Europe) compared to lithium disilicate counterparts (IPS e.max CAD; Ivoclar Vivadent AG) (El Ghoul et al., 2019b). Both endocrown materials in the latter study exhibited larger misfits in comparison to our current investigation. Such differences can be attributed to differences in specimen’s preparation and assessment method of misfit (µCT vs. replica method). In addition, different impression techniques (Kim et al., 2016a), type of finish line (Comlekoglu et al., 2009) and cement type (Fuzzi et al., 2017) have been reported to affect the marginal gap values with different ceramic materials.

Two-dimensional internal misfit significantly varied among groups ($p<0.001$) leading to partial rejection of the first null hypothesis. ILS and EMC exhibited significantly smaller internal misfit when compared to CS group ($p=0.001$). ILS is a fully crystallised material that is milled to final reconstruction dimensions and does not require post-milling sintering. The latter process was suggested to contribute to dimensional changes and marginal distortion of conventional LD glass-ceramic reconstructions (Vogel et al., 1997). However, our results did not show significant differences in the misfit values between ILS endocrowns and the conventional milled LD glass-ceramic endocrowns (EMC) ($p \geq 0.123$). This was in agreement with other studies reporting that crystallisation process resulted in a negligible (0.2–0.3%) volumetric shrinkage that had no effect on the accuracy of fitted crown reconstructions (Wiedhahn, 2007). In addition, the significantly inferior internal fit of CS, a fully cured material that requires no post-milling processing may indicate that crystallisation/sintering may not be solely responsible for such disparity in the accuracy of fit.

The roughness of the fitting surface of the endocrown might play a role in the ability to adequately seat restorations (Awada and Nathanson, 2015). This can be caused by the increase in surface irregularities which may increase micro-friction between endocrown and prepared tooth and alter the cement flow under pressure. In the current study, ILS showed the smoothest and most homogenous fitting surface, while CS reported the highest roughness measurements. However, no significant correlation was found between the roughness of endocrown's fitting surfaces and the internal misfit values ($p \geq 0.082$).

The literature is divided regarding as to whether LD glass-ceramics produce superior restoration fit when compared to RC materials (Coldea et al., 2013b, Goujat et al., 2018, Awada and Nathanson, 2015, Rippe et al., 2017, El Ghoul et al., 2019b, Coldea et al., 2013a). Machinability of the material is one of the most discussed parameters in this context. Studies that reported better machinability and adaptation of milled-sintered LD glass-ceramics attributed such findings to a low susceptibility to chipping and milling damage (Coldea et al., 2013a, Goujat et al., 2018, El Ghoul et al., 2019b). Contrarily, other studies reported superior adaptation of RC materials as a result of lower brittleness and better reproduction of fine surface details when compared to glass-ceramics (Awada and Nathanson, 2015, Rippe et al., 2017, de Paula Silveira et al., 2017).

Machinability of CAD/CAM materials and the marginal integrity of the reconstruction may largely influence the accuracy of fit. Edge fracture strength may be used to characterise the ability of the material to be milled in thin sections where the restoration is adapted to margins or fine details of the preparation. No significant difference was observed between edge fracture strength between CS and EMC materials (Pfeilschifter et al., 2018). Studies that reported inferior marginal and internal fit of LD glass- ceramics attributed such finding to the brittleness and friability of this material that led to inadvertent obliteration of the ultrafine details during the milling process (Awada and Nathanson, 2015, Rippe et al., 2017).. Conversely, RC materials exhibited a ductile material removal behaviour that ensured easy reproduction of details at the margins and fitting surface.

The accuracy of fit is one of the major determinants of clinical success of extra-coronal reconstructions. There is currently no consensus on the maximum threshold of marginal misfit. The clinical goal is to keep the marginal gap in the range of 25 to 40 µm (materials and devices, 1971). More often than, such accuracy of fit is far from achievable. Optimum retention has been achieved with 50-100 µm marginal misfit in reconstructions luted with resin cements, above which significant cement washout was observed (May et al., 2012). A marginal opening of ≤120 µm has been deemed clinically acceptable by McLean and Von Fraunhofer who examined in excess of a thousand crowns' 5-year clinical performance (McLean, 1971). One systematic review reported that the current CAD/CAM systems can produce extra-coronal reconstructions with <80 µm misfit (Boitelle et al., 2014). In this study, the mean marginal discrepancies for ILS, EMC and CS endocrowns were 77.8 µm, 91.3 µm and 92.4 µm, respectively. In previous studies, the marginal gap of CS and EMC endocrowns was in the range of 36.6-70.9 µm and 61.9-103.8 µm, respectively.

The presence of a minimum space (25 to 50 µm) between the restoration and the abutment allows an unhindered insertion and complete seating, and interposition of uniform, evenly distributed film of cement (Boitelle et al., 2014). In this study, the cement space was set at 80 µm for all experimental groups. The mean internal discrepancies for ILS, EMC and CS endocrowns were 97.1 µm, 98.1 µm and 138.7 µm, respectively. In previous studies, the internal gap of CS and EMC endocrowns was in the range of 116 µm and 105-182 µm, respectively (Shin et al., 2017, El Ghoul et al., 2019b). A study also reported an increase in marginal and internal discrepancies for EMC with deeper preparation of endocrown central retentive core (Shin et al., 2017).

One of the difficulties with using the µCT for restoration misfit is the inability to distinguish between the boundaries of restoration and the cement owing to close radiopacity of the two materials. In the present study, the use of a high-resolution µCT system allowed the differentiation between the two structures and we were able to report 2D pre- and post-bonding internal discrepancies where reference points and measurements were made manually. However, due to some limitations within the software and images, a consistent automatic identification of the cement space in a 3D level post-bonding could not be achieved. Thus, we only presented pre-bonding AIS findings in which CS group exhibited significantly higher mean AIS compared to the other groups ($p \leq 0.037$).

Resin luting is known to significantly increase the mechanical reliability of all-ceramic reconstructions (Guess et al., 2009). However, internal misfit exceeding 300 µm negated such an effect and resulted in spontaneous fracture of feldspathic full coverage crowns originating at the internal axio-occlusal line angles (May et al., 2012). This can be attributed to the substantial polymerisation stresses generated by the shrinkage of such large volume of resin luting cement. The axio-occlusal area in full coverage crowns corresponds to axio-cervical or cervico-pulpal areas in endocrowns owing to the difference in reconstruction configuration. In this study, ILS and EMC endocrowns demonstrated smaller misfit in such areas. Their misfit values were in the range of 75-109 µm. Studies reported that full coverage crowns with internal misfit values in similar areas between 50-100 µm exhibited highest fracture strength compared to larger internal misfits (May et al., 2012). Having all post-bonding internal misfit readings less than 300 µm in this study, we expect that resin luting cement will maintain its strengthening effect on the studied restorative systems.

Biomechanical reliability, optimum adaptation and aesthetics are the key requirements for a successful restorative system. The evidence points toward optimum biomechanical performance of the investigated LD glass ceramics. In this study, we have confirmed, using an advanced, non-invasive technique, that the three investigated CAD/CAM materials achieved clinically acceptable marginal gaps. Further, machinable, partially- and fully-crystallised LD glass-ceramics exhibited optimum internal adaptation. However, CAD/CAM RCs may require further optimisation in terms of material composition or machinability in order to ameliorate the increased internal gap observed in endocrowns investigated in this study.

4.7 Conclusions

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

- Adhesive bonding of the endocrowns to premolar teeth did not have a significant, adverse effect on the marginal and internal adaptation,
- The CAD/CAM material had no effect on the marginal adaptation of endocrown,
- Both, partially- and fully-crystallised LD glass ceramics exhibited superior internal adaptation compared to a CAD/CAM RC material,
- Endocrowns fabricated from the machinable, fully-crystallised LD glass ceramic exhibited the most homogenous fitting surface and the smoothest roughness profile, and
- No correlation was found between 2D internal misfit and the surface roughness profile of endocrowns

Chapter 5

Evaluation of remaining coronal dentine walls on the mechanical behaviour of a maxillary premolar restored by an endocrown: 3D Finite Element Analysis

5.1 Introduction

Preserving the maximum amount of remaining tooth structure through minimal invasive preparation techniques, has become the gold standard for restoring teeth (Plotino et al., 2008, Angeletaki et al., 2016). Endodontically treated teeth (ETT) with extensive coronal damage usually present a greater risk of failure or fracture than vital teeth, this is mainly because of the loss of structural integrity and reduced protection due to a lack of neurosensory feedback mechanism (Sedgley and Messer, 1992, Tang et al., 2010). Therefore, the treatment of such teeth should aim to protect and reinforce the remaining sound tooth structure.

Fibre post crown preparations require additional removal of sound tooth structure and may cause further weakening of tooth structure (Schwartz and Robbins, 2004, Heydecke and Peters, 2002). In addition, in some cases, extra treatment procedures such as crown lengthening are recommended to gain a sufficient ferrule height, which could result in further reduction of the tooth fracture resistance. On the other hand, endocrown preparation has the advantage of preserving the maximum tooth structure, reducing the need for additional retentive techniques and saving treatment time and cost as fewer procedural steps are required (Bindl et al., 2005, Belleflamme et al., 2017).

The importance of obtaining sufficient amount of remaining coronal tooth structure in restoring ETT has been emphasised in the literature (Tang et al., 2010). Preserving coronal tissue remnant and adding a ferrule design into the crown preparation are reported to have a significant effect on the biomechanical behaviour of ETT restored with post retained crowns (Ma et al., 2009, Juloski et al., 2014a). However, in clinical situations, obtaining sufficient circumferential coronal dentine in all walls is not always achievable due to the extent of carious lesions or fracture. As opposed to post retained crowns, endocrown restorations do not require an additional ferrule preparation design, since endocrown success depends mainly on adhesive retention (Bindl et al., 2005). However, remaining coronal dentine could be essential for supporting the endocrown restoration and distributing stress forces more evenly throughout the tooth-restoration complex (Zhu et al., 2017).

Currently, there is very little information regarding the amount of remaining coronal walls and the effect this has on the prognosis of highly compromised teeth, especially with endocrown restorations. Few *in-vitro* studies have investigated this matter on partial ferrule with post retained crowns. A study (Al-Wahadni and Gutteridge, 2002) investigated partial ferrule with only the facial wall and concluded that a ferrule of 3 mm or more enhanced the fracture resistance compared with no ferrule. Another study reported that teeth with 2 mm ferrule and no proximal walls showed the lowest fracture resistance (Naumann et al., 2006). Moreover, a study found statistically significant lower fracture resistance in teeth with remaining 2 mm buccal and lingual height and 0.5mm proximal walls, in comparison to other cases (Tan et al., 2005b). On the other hand, a study reported that teeth with residual proximal or buccal walls showed lower fracture resistance compared to cases with remaining palatal walls (Ng et al., 2006). In a recent study, it was concluded that root canal treated maxillary incisors with a complete 2-mm ferrule were more resistant to fracture than teeth with a 2-mm ferrule and 1 missing interproximal wall. However it was found that 3 or 4 mm of increased wall height would compensate for the missing interproximal wall (Pantaleón et al., 2018). Although this is a clinically important matter that could significantly affect the treatment decision or plan for different clinical scenarios, there is still lack of information and guidelines with few studies presenting variable results. Therefore, it is recommended that more studies are required to clarify the relation between the remaining numbers of coronal walls and restoration failures (Yang et al., 2015).

Moreover, because of the large variability of the results obtained from previous *in-vitro* studies (Al-Wahadni and Gutteridge, 2002, Naumann et al., 2006, Tan et al., 2005b), an increasing number of investigations of teeth and restorations are based on finite element (FE) analysis (Dejak and Mlotkowski, 2013, Helal and Wang, 2019, Lin et al., 2009). It is a proven useful tool in understanding biomechanics in restorative dentistry (Piccioni et al., 2013). FE method can be useful in avoiding the random variability in results and the ability to reproduce results without affecting the physical properties of the samples involved (Piccioni et al., 2013, Borcic and Braut, 2012). Moreover, FE analysis can provide stress distributions for the entire tooth-restoration complex, rather than reporting a single value of failure load (Lin et al., 2011, Aversa et al., 2009). These internal stresses are extremely difficult to measure using an experimental approach.

So far, FE studies have reported non-uniform stress distribution patterns in the complex models of restored ETT especially when post crowns are used (Sorrentino et al., 2007, Fu et al., 2010). The stress concentration and distribution among such teeth depended on variable factors such as the magnitude and direction of the applied external loads, geometry of structure, characteristics of the interfaces, and materials used (Fu et al., 2010, Caldas et al., 2018). The importance of minimising stresses within restored teeth and recreating the original stress distribution of a sound tooth have been emphasised (Zhu et al., 2017, Sorrentino et al., 2007). Currently, little information is known regarding stress distribution patterns in teeth restored with endocrowns and the influence of variable preparation designs and materials used.

Although, some previous studies investigated this topic on post retained crowns, no studies are available on the effect of the number and location of remaining coronal walls, and materials used on the mechanical behaviour of ETT restored with endocrowns.

5.2 Aim of Study

The aims of this study are:

To determine the stress distribution and risk of failure of endodontically treated (ET) maxillary premolars restored with endocrown presenting various amounts and locations of remaining coronal tooth structure, using three-dimensional FE method.

To compare stress distribution between sound teeth and teeth with different amount and location of remaining tooth structure restored with endocrowns using two different restorative materials.

5.3 Null hypothesis:

The amount and location of remaining coronal tooth structure, and restorative material used will not affect the stress distribution and risk of failure in ET maxillary premolars restored with endocrowns.

5.4 Methodology

5.4.1 Geometrical model design

Three-dimensional geometry of a single rooted premolar constructed from a Computerised Tomography (CT) scan of a natural tooth was obtained from an open-access online database (Vasco et al., 2015). The model parts were imported into computer-aided design software (SolidWorks 2019, Dassault Systemes, SolidWorks Corps) for modelling the different experimental groups.

A section of the bone and soft tissue were added to the CAD model. This was 20 mm in height, 10 mm in diameter bucco-lingually, and 14mm in diameter mesio-distally. The cortical layer of bone is 2 mm thick while the remaining bone was modelled as trabecular bone. This section was connected to the CAD model by a 0.2 mm thick periodontal ligament (PDL) and 0.5 mm thick cortical bone. The model of sound tooth with PDL and bone simulation was considered as model S, the control model (Figure 31).

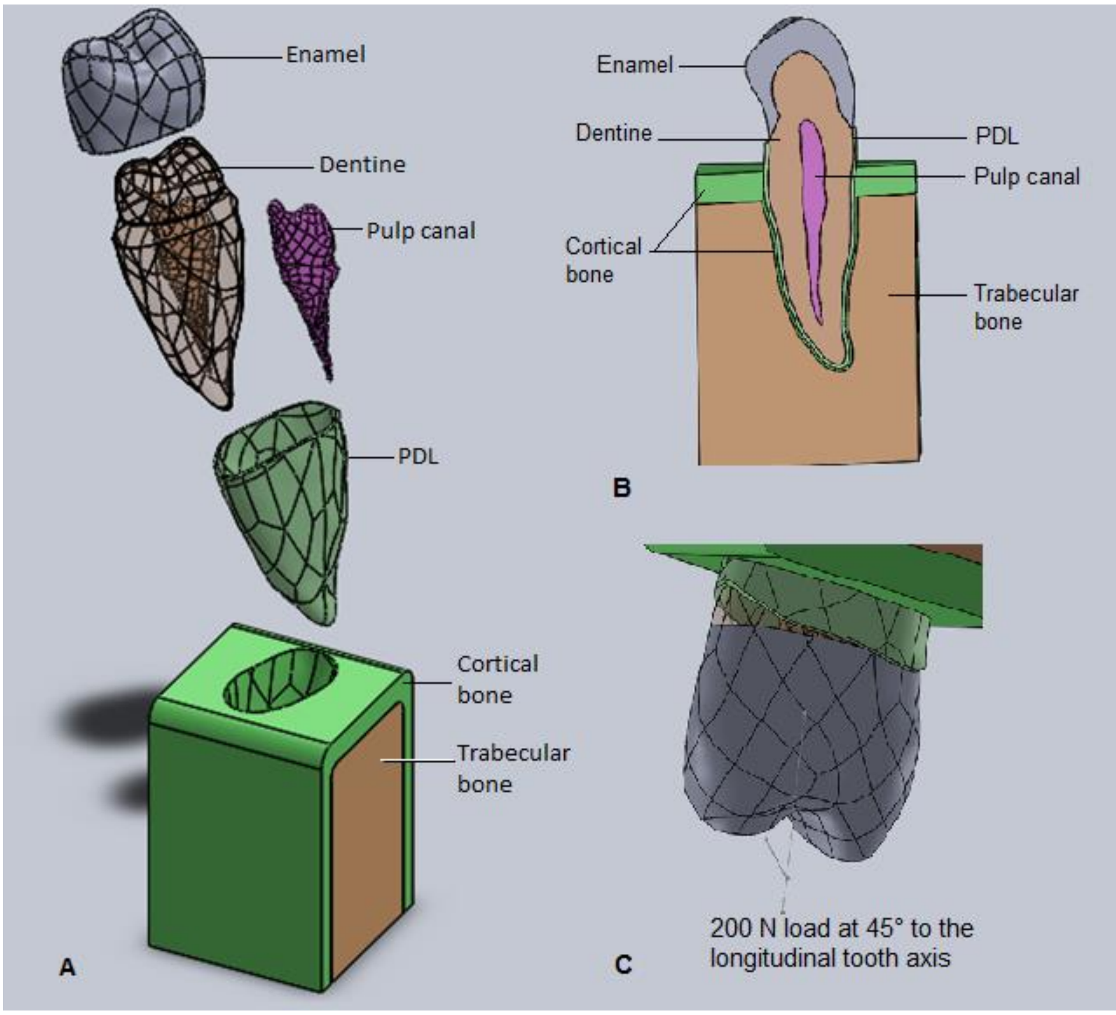


Figure 31 Representation of the 3-dimentional components of model S (sound maxillary premolar and surrounding tissue) and the direction of static load applied on tooth occlusal surface. A: exploded view, B: sectional view, C: force direction.

Six solid-models representing different degrees of coronal tissue loss were generated from model S to create geometrical models of restored teeth (SolidWorks 2019, Dassault Systemes, SolidWorks Corps). The solid-models were represented in a consistent manner, with the dental remnant height and location as the unique geometry variable. The Cemento-Enamel Junction (CEJ) served as the circumferential reference for the linear measurement of the remaining coronal heights for each model. Models were generated according to the following descriptions (Figure 32):

Model CR: (Complete remaining 2-mm-high coronal tissue),

Model IR_MD: (2-mm-high incomplete coronal tissue remaining interproximal axial walls), Model IR_BP: (2-mm-high incomplete coronal tissue remaining buccal and palatal walls),

Model IR_P: (2-mm-high incomplete coronal tissue remaining palatal wall),

Model IR_B: (2-mm-high incomplete coronal tissue remaining buccal wall),

Model NR: (no remaining coronal tissue)

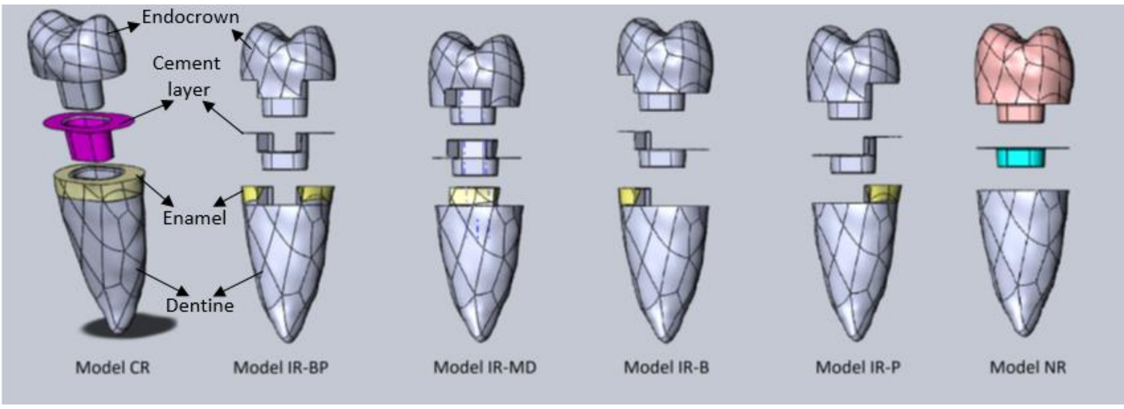


Figure 32 Representative images of the geometry of different experimental models presenting a maxillary premolar with different amounts and location of remaining tooth structure restored by CAD/CAM endocrown restorations.

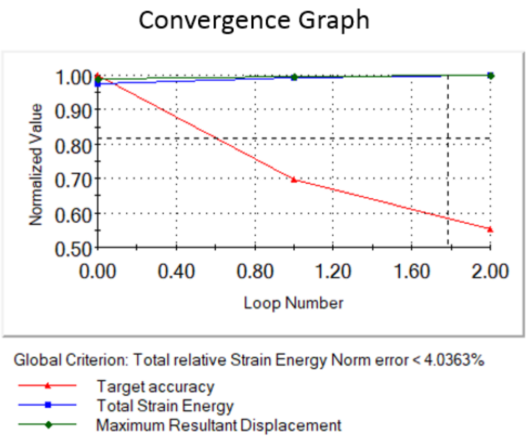
The pulpal space was filled with gutta-percha and endocrown restorations were added to the models with tissue loss following standard clinical preparation process. The tooth preparation consisted of a butt joint margin preparation design according to the remaining tooth structure. The central retention cavity extended 4 mm in depth from the highest point of the occlusal floor (or 2 mm from CEJ) with rounded internal line angles. This central retentive cavity was prepared in an oval shape following the original shape of pulp chamber with 8 degree convergence angle and rounded edges. The endocrown reconstruction was modelled to fit the abutment (Figure 32).

The cement interface between the prepared teeth and endocrown was simulated by a layer with an average thickness of 50 μm (Chazine et al., 2012, Juloski et al., 2014a).

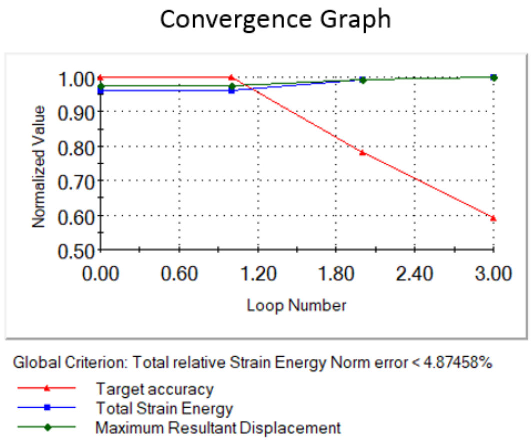
5.4.2 FE model generation and analysis

The geometrical models described above (6 restored teeth and 1 sound tooth) were imported to the Finite Elements Analysis (FEA) software for simulation (SolidWorks 2019, Dassault Systemes, SolidWorks Corps). A total of 13 finite element models were generated, in which two restorative endocrown materials were investigated for each of the 6 experimental restored models: a resin based composite endocrown and a lithium disilicate glass ceramic endocrown.

Parabolic tetrahedral solid elements were used in the meshing design of all experimental models. The meshes were generated through a convergence test of 5% strain energy and displacement variation control (Figure 33, Figure 34). The mesh was checked for element quality and refined in areas of interest. The number of total elements and nodes in experimental models varied between 122880 to 73114 elements, and 250916 to 128981 nodes.



Model CR



Model IR-P

Figure 33 Line graphs presenting the convergence test results for models CR (left), and models IR-BP (right), when 5% strain energy control is applied.

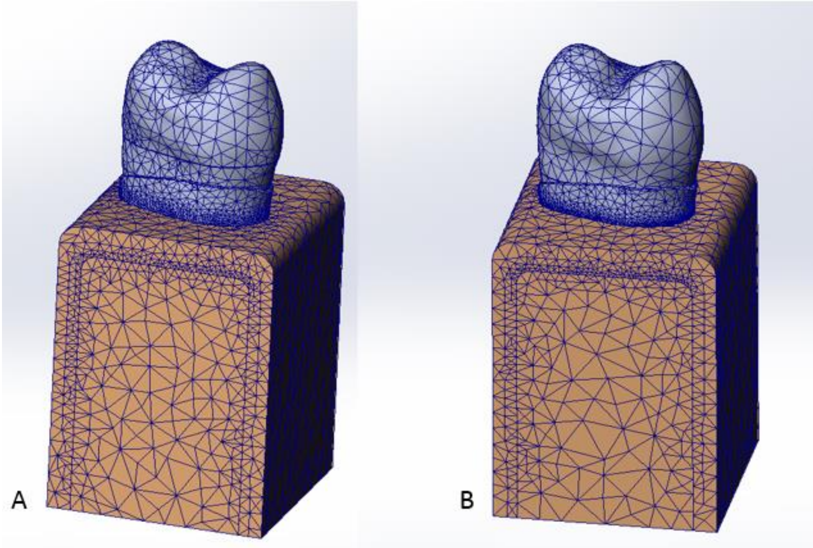


Figure 34 Representative image of the mesh design of models: A: model CR, and B: model S.

5.4.3 Material Properties

The natural tissues and the restorative materials used in this study, were considered linear, elastic, homogenous and isotropic. The material properties of the tooth tissue, bone, PDL, restorative materials and cements were assigned according to the literature as shown in Table 17 (Holmes et al., 1996, Chang et al., 2018, Dejak et al., 2007, Wu et al., 2018).

Table 17 Isotropic, mechanical properties adopted for simulated tooth tissue and restorative materials

Material/ structure	Young's Modulus (GPa)	Poisson's ratio
Enamel	84.1	0.33
Dentine	18.6	0.31
Resin cement	8.3	0.35
Lithium disilicate crown	95	0.3
Resin based composite crown	12.8	0.3

Material/ structure	Young's Modulus (GPa)	Poisson's ratio
PDL	0.00427	0.45
Cortical bone	13.7	0.3
Cancellous bone	1.37	0.3
Gutta-percha	140	0.45

Ideal adherence was assumed between structures (ceramic with cement, and cement with dentine). Endocrowns elements were coupled to the material properties of lithium disilicate glass ceramic or resin based composite while the dentine-endocrown interface elements were coupled to the material properties of resin cement.

5.4.4 Load and External Conditions

All models received an oblique force of 200 N at 45° to the longitudinal tooth axis at the incline surface of the buccal cusp to simulate masticatory forces (Figure 31). In each model, the movement of the mesial, distal and bottom surfaces of the trabecular bone were restricted.

5.4.5 Presentation of the results

Maximum Principal Stress values:

Due to the relatively low tensile strength of dentine, restored teeth are more prone to fracture under tensile stress (Sano et al., 1994, Asmussen et al., 2005). Thus, this study focused on analysis of the distribution of maximum principal stress in the cervical dentine of the root around the endocrown restoration, which is the area most susceptible to failure initiation (Zarone et al., 2006). In addition, an evaluation of the maximum principal stress distribution on enamel, ceramic endocrowns, resin endocrowns, and resin cement was performed. To better demonstrate the difference between groups, the 30 highest stress values were selected in the analysed structures or area of interest for quantitative comparison. The average of these values was used instead of reporting the highest single peak value which could be misleading. Stress distribution in different structures was presented to visualise the overall mechanical behaviour.

Risk of debonding assessment:

To assess the risk of debonding, the maximum shear stress in the different interfaces of the cement layer were calculated and compared to ultimate shear stress values of corresponding interfaces from literature (Table 18).

Table 18 Ultimate Shear strength for different interfaces of the cement layer, in addition to the Ultimate Tensile and Compressive strength of Dentine, (N/mm^2 (MPa)).

Cement Interfaces/ Dentine	Ultimate shear strength
Resin cement/Tooth	29.1(Jun, 2011)
Resin cement/ Resin composite Endocrown	15 (Secilmis et al., 2016)
Resin cement/ Ceramic Endocrown	27(Lise et al., 2015)

Risk of fracture assessment:

The Factor of Safety (FOS) theory was used to assess the safety of the models based on the Mohr–Coulomb failure criterion at the region of interest (cervical dentine) (Caldas et al., 2018). This theory can be used to predict fracture in brittle materials with different compressive and tensile properties. The Mohr–Coulomb theory predicts failure to occur when the combination of the maximum tensile principal stress and the minimum compressive principal stress exceed their respective stress limits. The dentine ultimate tensile strength (UTS) and ultimate compressive strength (UCS) are 105 MPa and 298 MPa respectively, as reported from the literature (Craig and Peyton, 1958, Miguez et al., 2004). The Mohr–Coulomb stress ratio (σ_{MC}) is calculated as:

$$\sigma_{MC} = \frac{\sigma_{max}}{UTS} + \frac{|\sigma_{min}|}{UCS}$$

Equation 1

Accordingly, the FOS is calculated as the following:

$$FOS = \left(\frac{\sigma_{max}}{UTS} + \frac{|\sigma_{min}|}{UCS}\right)^{-1}$$

Equation 2

Where σ_{max} is the maximum tensile principal stress, and σ_{min} is the minimum compressive principal stress. A factor of safety less than 1 at a location indicates that the material at that location has failed, while a factor of safety larger than 1 at a location indicates that the material at that location is safe. The material at a location will start to fail if you apply new loads equal to the current loads multiplied by the resulting factor of safety, and assuming that the stresses/strains remain in the linear range.

5.5 Results:

5.5.1 Stress distribution in sound tooth:

The maximum principal stress in model S (sound tooth) was concentrated in both enamel and dentine (Figure 35, Figure 36). In enamel, the stress was concentrated in the loading area occlusally and at the cervical area. The maximum principal stress in dentine was concentrated mainly in the coronal dentine with lower stress distributed to the coronal third of root dentine (Figure 35, Figure 36).

5.5.2 Stress distribution in restored models:

In restored models, the maximum principal stress was concentrated in endocrown, enamel, dentine, and cement layer. In all restored models, the transfer of stress apically from coronal dentine towards the root dentine was increased compared with model S (Figure 35, Figure 36). Model CR showed lower cervical dentine stress concentration when compared to all other models (Table 19). Moreover, models with two remaining walls showed lower cervical stress concentration compared to models with one or no remaining walls (Figure 35, Figure 36 and Table 19).

When compared to ceramic models, resin models showed lower stress concentration in cervical root dentine and higher stress concentration on enamel (Table 19). The maximum principal stress in the ceramic endocrowns was concentrated in the loading area occlusally, cervical area, and on the central retainer. Resin based composite endocrowns showed similar stress distribution to ceramic-based, however, less stress was distributed towards the central retainer area with lower stress levels overall (Figure 35, Figure 36 and Table 19).

Regarding stress distribution in the resin cement layer, higher stress was generally reported in resin models compared to ceramic models (Table 19). Models CR showed the most homogenous stress distribution among cement layers and generally lower values compared to other models with incomplete remaining coronal walls (Figure 35, Figure 36 and Table 19).

Models NR, IR-P and IR-MD showed higher stress concentration at the buccal and palatal marginal areas, in addition to the axial walls and the cervico-axial angle of the cement layer. Model IR-P with both materials showed the highest peak stress in the cement layer among all other models (Figure 35, Figure 36 and Table 19).

Table 19 Average of maximum principal stress high peaks at cervical root dentine, enamel, endocrown, and cement layer under 200 N oblique load (N/mm^2 (MPa)).

Model/ Material	Cervical root dentine		Enamel		Endocrown		Cement	
	Resin-based	Lithium Disilicate	Resin-based	Lithium Disilicate	Resin-based	Lithium Disilicate	Resin-based	Lithium Disilicate
1-Model S	34		52					
2-Model CR	31	31	42	35	38	54	9	9
3-Model IR-BP	32	35	34	25	32	50	16	12
4-Model IR-MD	31	32	43	21	36	47	17	10
5-Model IR-B	33	43	25	13	41	52	13	9
6-Model IR-P	35	41	47	36	45	52	17	14
7-Model NR	34	40			37	44	10	7

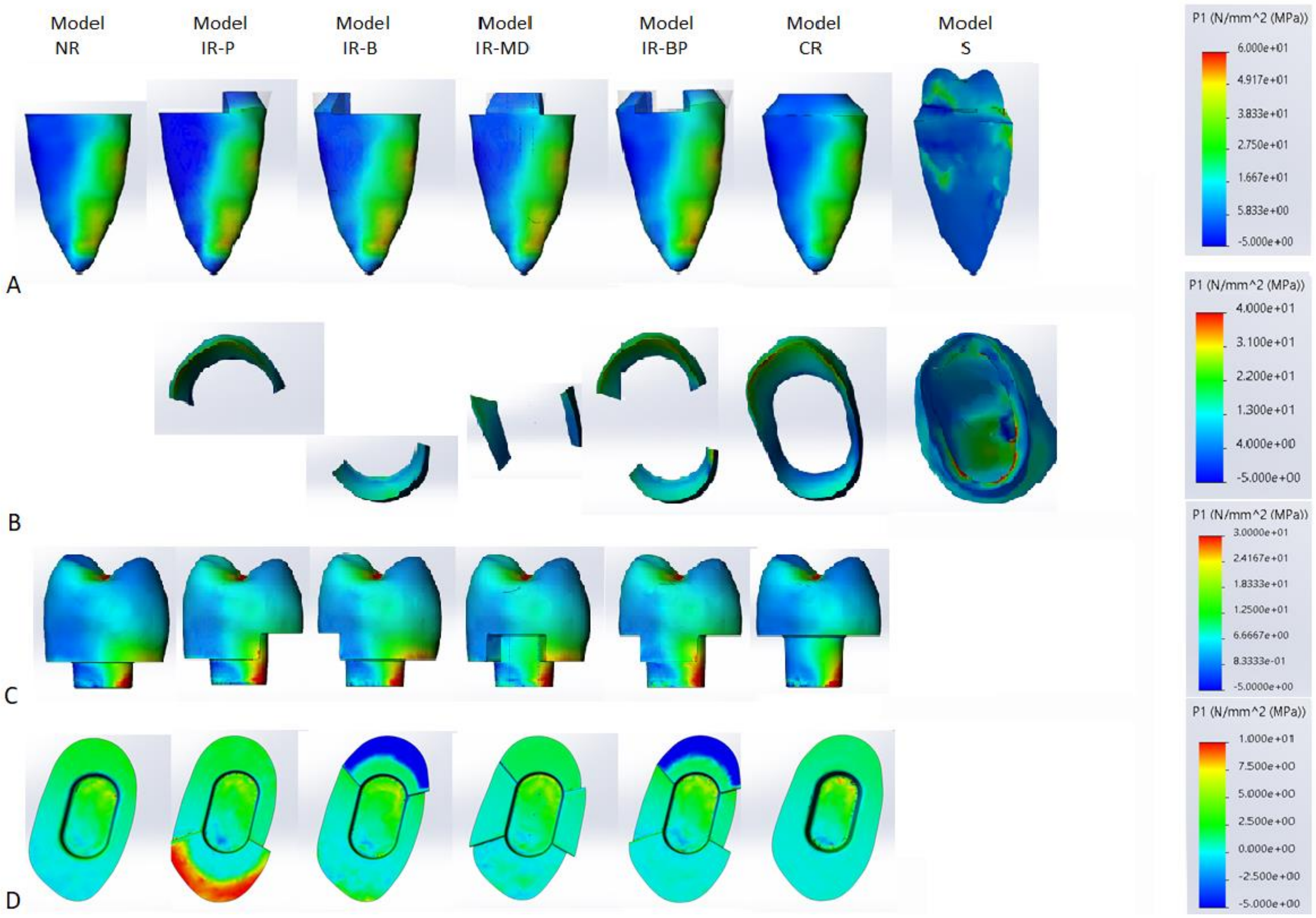


Figure 35 Maximum Principal Stress distributions (MPa) in sound tooth and teeth restored with lithium disilicate glass ceramic endocrowns. A: dentine, B: enamel, C: restoration, D: cement layer.

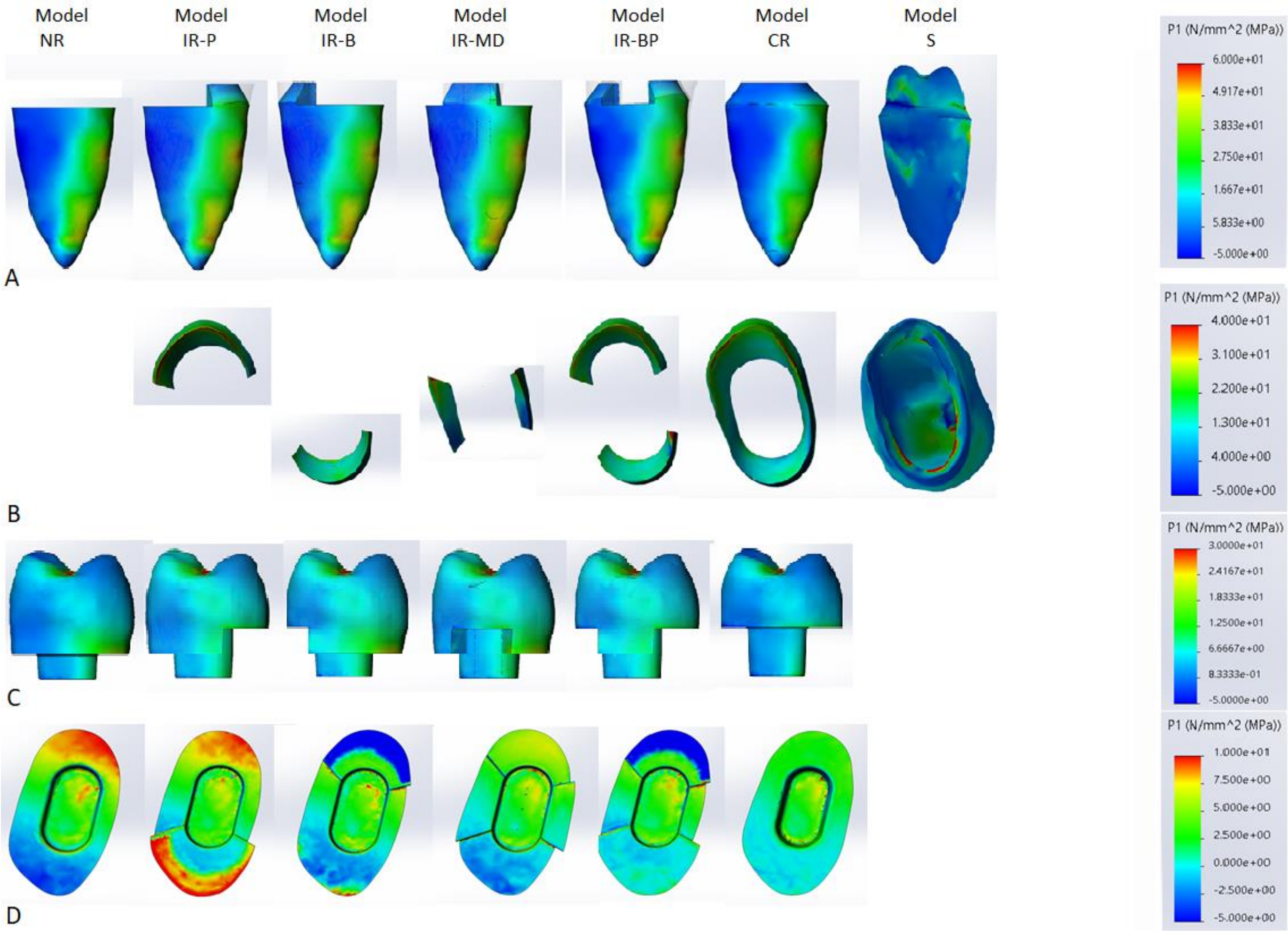


Figure 36 Maximum Principal Stress distributions (MPa) in natural tooth and teeth restored with resin based composite endocrowns. A: dentine, B: enamel, C: restoration, D: cement layer

5.5.3 Maximum shear stress values of cement interface surfaces:

The maximum shear stress values of all interfaces were below the ultimate shear strength of the corresponding interfaces for both endocrown materials (Table 20).

Table 20 Maximum values of shear stress (MPa), and the (risk of debonding %) at cement-tooth interface and cement-endocrown interface under 200 N oblique load.

Model	Cement-tooth		Cement-endocrown	
	Resin-based	Lithium Disilicate	Resin-based	Lithium Disilicate
	Max-shear	Max-shear	Max-shear	Max-shear
Model CR	2.2 (8%)	2.4 (8%)	2.4 (16%)	1.6 (6%)
Model IR-BP	3.1 (11%)	2 (7%)	4.1 (27%)	1.7 (6%)
Model IR-MD	6.4 (22%)	4.4 (15%)	3 (20%)	2 (7%)
Model IR-B	3.5 (12%)	2 (7%)	5.3 (35%)	2.9 (11%)
Model IR-P	2 (7%)	1.4 (5%)	2.2 (15%)	1.3 (5%)
Model NR	1.7 (6%)	1.6 (6%)	6 (40%)	2 (7%)

5.5.4 Factor of Safety (FOS):

The FOS for different models at the cervical dentine was influenced by the amount of remaining coronal dentine and the restorative material used (Figure 37). Teeth restored with resin endocrowns presented FOS values similar to sound tooth and higher compared to teeth restored with ceramic endocrowns. Models CR, IR-BP, and IR-MB showed FOS values close to sound tooth. However, models with minimal or no remaining dentine walls showed a decrease in FOS values, which indicates a higher potential for crack initiation at the cervical dentine of the root around the endocrown restoration. The FEA indicated lower risk of fracture for models with more amount of remaining coronal dentine and models restored with resin endocrowns.

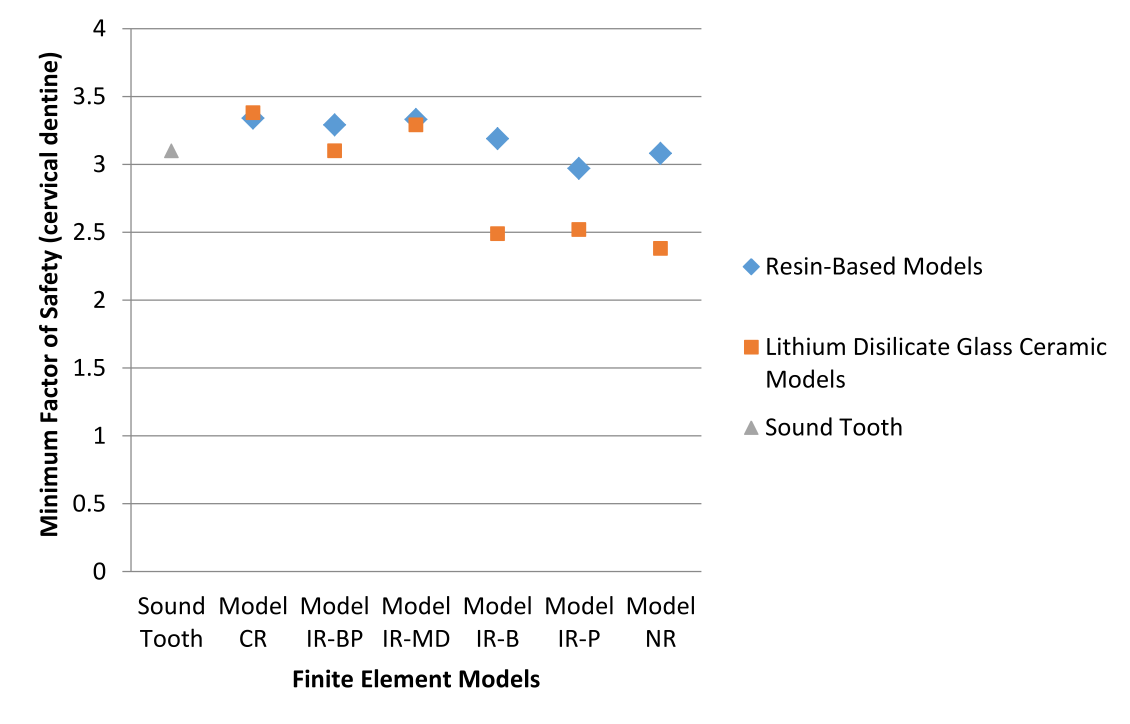


Figure 37 A linear graph presenting minimal factor of safety (FOS) for cervical root dentine in different experimental models and sound tooth.

5.6 Discussion:

Structural loss with complete cusp fracture is common in ET premolars. Endocrowns have recently been introduced as an alternative treatment for ETT (Bindl et al., 2005). Their simplified design does not require excessive macro-retentive tooth preparation and hence can preserve the remaining amount of sound tooth structure (Bindl et al., 2005, Belleflamme et al., 2017). The current study demonstrated that preserving the maximum amount of remaining coronal tissue can be beneficial in supporting the tooth restoration complex. However, when preserving circumferential coronal tissue is not feasible, the amount and location of remaining tissue, and the restorative material used influenced the stress distribution in premolars restored with endocrown, thus rejecting the null hypothesis.

In this study, we used the Finite Element (FE) method, which is a method that can analyse complex structures and calculate the stress distribution within these structures (Dartora et al., 2018). FE analysis can be useful in investigating different aspects related to endocrown restorations due to the enormous variability of the data received from *in-vitro* studies (Aktas et al., 2018, Altier et al., 2018, Biacchi and Basting, 2012). The advances in imaging techniques and the progress of structural FE modelling and meshing, resulted in more accurate and reliable biomechanical analysis of structures using FE analysis. The accuracy of the model used in this technique is what determines the accuracy of the results obtained. Our model was obtained from a CT scan of a natural premolar tooth, ensuring more accurate clinical simulation and representation of the internal parts (Vasco et al., 2015). In addition, the simplicity of the endocrown restoration design and the presence of only one cement layer compared to the complex multiple interfaces presented in the post crown restorations, makes the former more reliable for investigation using FEA simulation methods (Lin et al., 2013).

The accuracy of material properties assigned to the structures under investigation is a critical factor in FE studies. Different researchers have used different physical characteristics of dental tissues (Dejak and Mlotkowski, 2013, Zhu et al., 2020, Juloski et al., 2014a). In the current study, all materials were considered homogenous and isotropic. Studies found that, although some heterogeneity and anisotropy has been reported for dentine, the stiffness response of dentine seems to be only mildly anisotropic (Huo, 2005). Thus most available studies including the current study considered dentine to be an isotropic material. The only tissue for which the linearity may be too strong an assumption in the range of deformations observed is the PDL which stiffness increases with stress. However, due to the type of data investigated, regions of interest, and the comparative purpose of the study, a simplified simulation of the complex PDL structure was conducted in the current study in order to reduce computational complexity without affecting the final conclusions. A more comprehensive simulation of PDL fibres might be critical in studies investigating tooth movement as in orthodontic treatments (Cattaneo et al., 2005). On the other hand, it should be noted that the specific mechanical behaviour and properties of the complex PDL structure are still considered poorly understood, thus most available studies conducted a simplified linear analysis for tooth models with PDL structure.

In the clinical intra-oral environment, restored teeth will be subjected to fatigue stress through repeated cyclic loading. This could lead to the development of microcracks, hence causing failure of the restored tooth (Ausiello et al., 2001). These microcracks will form at areas of highest stress and lowest local strength. It was reported that similar areas of high stress concentration and similar failure patterns were observed in cases tested under static and fatigue loading conditions (Ferreira et al., 1999, Found and Quaresimin, 2002, De Iorio et al., 2002). Therefore, static linear tests can be reliable in extrapolating data about the relative susceptibility of restored teeth to fatigue loading conditions. Hence, it can be assumed that restored teeth showing homogeneous stress distribution under static analysis might show a higher fatigue resistance in clinical situations.

Von Mises stress or maximum principal stress can be used in FE analysis to report stress concentration and distribution in models. The Von Mises criterion is relevant in models with ductile materials of similar tensile and compressive strength (De Groot et al., 1987), however materials such as ceramics, cements and resin composites presenting brittle behaviour were used in the current study. Moreover, it is reported that dentine exhibits tensile strength values significantly lower than its compressive strength (Craig and Powers, 2002). Thus, in the current study, the use of the maximum principal stress to analyse stress results was adopted (Ichim et al., 2006, Nakamura et al., 2006). Accordingly, Mohr–Coulomb failure theory was used to analyse the risk of failure in dentine. This theory can be used to predict fracture in brittle materials with different compressive and tensile properties (Pérez-González et al., 2011). Mohr–Coulomb theory states that failure occurs when the combination of the maximum and minimum principal stress equals or exceeds the stress limits (tensile or compressive strengths).

Previous studies reported that the area for failure initiation of restored teeth predicted by Von Mises criterion was in the crown, however, the Mohr–Coulomb criteria along with other long-established brittle criteria reported failure initiation at the cervical dentine area under tensile stresses (Pérez-González et al., 2011). Moreover, *in-vitro* studies reported that clinical fracture of restored teeth is usually initiated at the cervical area of dentine around the indirect restoration (Zarone et al., 2006). Therefore, the cervical dentine area surrounding the endocrown restoration was considered as the region of interest for stress analysis and failure prediction.

On the other hand, previous studies revealed that the maximum shear stresses were primarily located at the tooth/restoration or tooth/post interfaces (Asmussen et al., 2005). This indicates that while tensile stresses will affect the risk of root fracture, the shear stresses will influence the risk of restoration debonding. Hence, shear stress can lead to rupture of the tooth/restoration interface and eventually cause loss of retention and debonding. Therefore, in the current study results of shear stress in the restoration-cement-dentine interfaces were reported and compared to their corresponding ultimate bond strengths in order to evaluate the risk of debonding (Pegoretti et al., 2002, Asmussen et al., 2005).

In this study, 200 N load at 45 degree angle to the long access of the tooth was applied to simulate the clinical masticatory forces, as previous studies reported that oblique forces present more detrimental effects on restored teeth compared to vertical forces, hence simulating the worst case scenario (Palamara et al., 2000, Yamanel et al., 2009). Six different scenarios presenting different amounts and location of remaining coronal dentine were investigated to study the efficiency of endocrown in restoring maxillary premolars (Figure 32). When 2mm circumferential coronal dentine was preserved, the maximum principal stress values in dentine decreased and were concentrated more coronally compared to all other cases with partial or no remaining coronal dentine (Table 19 and Figure 35, Figure 36). This was in agreement with a previous study, in which more amount of remaining coronal dentine reported less stress values in tooth structure (Zhu et al., 2017). In addition, models with 2mm circumferential coronal dentine showed generally lower stress values throughout the cement layer, compared with partial remaining coronal dentine (Table 19, Table 20). However, when compared to sound tooth, experimental models with lower amount of remaining coronal dentine transferred more stress in an apical direction towards root dentine indicating a higher risk of catastrophic failure for restored teeth compared to sound teeth (Figure 35, Figure 36), which was in agreement with previous *in-vitro* studies (Guo et al., 2016b).

Our study revealed that none of the models reported a maximum shear stress at the cement interfaces beyond the ultimate shear strength of their corresponding interfaces (Table 20). However, models IR-MD, NR, and IR-P showed higher stress values compared to other models (Table 19, Table 20). Moreover, these models presented higher stress concentration at the buccal and palatal margins, cervico-axial and axio-pulpal angles (Figure 35, Figure 36). High stress concentration in the internal angles of the cement layer (cervico-axial and axio-pulpal) could initiate crack propagation, which will eventually result in adhesive failure or tooth fracture due to stress concentration at the crack initiation tip (Zhang et al., 2009, May et al., 2012). This indicates that in cases where no buccal and palatal walls are remaining to support the endocrown restoration, premature or early de-bonding could occur; hence endocrowns should be avoided in such cases especially with resin composite based materials. Modifications to the restoration design or extra treatment measurements such as crown lengthening could be necessary in such cases. On the other hand, the maximum principal and shear stress of models with circumferential coronal walls or remaining buccal and palatal walls indicates reliability of endocrown restoration in reconstructing such cases. The reliability of adhesive bonding between endocrowns and tooth structure is very crucial as previous clinical studies reported that bonding failure was the main cause of failure in endocrown restored teeth (Bindl et al., 2005).

The previous findings might suggest that extra smoothening and rounding of the internal edges might lead to less stress concentration at the cement layer and surrounding dentine, therefore reduce the risk of failure. However a previous study reported that rounding the central retainer of the endocrown by placing resin or glass-ionomers instead of designing central retainer shape on the basis of the anatomical form of the pulp chamber, would result in greater stress concentrations, rather than reduced concentrations (Zhu et al., 2020). This was justified by the fact that the low-elastic modulus resin used in their study was small in size; thus, it could not dissipate a large amount of energy (Zhu et al., 2020). This topic will need further investigation in the future due to the different findings reported.

When comparing different restorative materials, resin models reported higher maximum principal stress and shear stress values at the cement layers compared to ceramic models. (Table 19, Table 20). This indicates that resin endocrowns are more prone to dislodgement failure at a later stage. In cases with minimal or incomplete remaining coronal dentine, our results indicate that ceramic endocrown could enhance the reliability of the adhesive interface where cracks are frequently initiated. Previous FE studies reported that a restorative material with higher modulus of elasticity will result in better bonding efficiency compared to materials with lower modulus of elasticity (Zhu et al., 2017). Moreover, *in-vitro* studies reported that more microleakage may be expected if the endocrown is made of resin based material (El-Damanhoury et al., 2015). The bonding efficiency and marginal integrity are crucial for the long term prognosis of the tooth (Felton et al., 1991), as failure in the luting cement especially at the marginal area will cause direct contact with the oral environment, which might lead to secondary caries and restoration failure.

On the other hand, resin models showed lower maximum principal stress concentration in the endocrown especially at the central extension part (Table 19 and Figure 35, Figure 36). This caused lower transfer of the maximum principal stress to the cervical dentine structure at the area around the endocrown central retainer (Table 19). These findings are clinically significant since previous studies reported that clinical fracture of indirect restorations is usually initiated at the tooth/restoration interface, especially at the internal angles or the central region opposite to load application (Kelly et al., 2010, May et al., 2012, May et al., 2015). According to our results, this indicates that teeth restored with resin endocrowns will have a lower risk of catastrophic failures compared to ceramic endocrowns (Figure 37). Previous studies also reported that teeth restored with restorations made of composite resin demonstrated better fatigue resistance compared with those made of porcelains or ceramics (Magne and Knezevic, 2009b, Magne and Knezevic, 2009a). In addition, our FOS results indicated lower risk of catastrophic failure for models CR, IR-BP, IR-MD compared to models IR-B, IR-P, and NR (Figure 37).

This study presented several limitations in regard to load conditions, adhesive layers and material properties. All bonded parts were assumed to be ideally bonded due to numeric convergence considerations. As mentioned earlier, a simplified linear simulation of the complex PDL structure was conducted. Some simplifications and assumptions are commonly used in dental FEA studies due to the elaborate dental models investigated, large anatomical variability, the difficulty involved in obtaining the mechanical properties of the tooth's constituent materials, and the complex load and boundary conditions in dental models. Biomechanical FE studies are often used to determine the tendency and difference among various factors instead of calculating the absolute value due to such unavoidable simplifications. Accordingly, due to the comparative nature of the study and given that the FOS at the regions of interest is above 2, this indicates that such limitations or the lack of model validity should not affect the representative tendency of the current results. The high FOS indicates that the tested models will still be safe even if there was a possibility of error in the results by a factor of 2.

The FE method has proven itself an extremely powerful tool in addressing many biomedical problems that are challenging for more conventional methods because of structural and material complexity. However, FE results and conclusions should be evaluated in combination with laboratory and clinical studies in order to investigate the long-term clinical efficiency of endocrowns.

5.7 Conclusion

Within the limitations of this FEA study, our results indicate that a conservative endocrown preparation design with 2mm remaining circumferential coronal tooth structure will reduce the maximum principal stress concentration on dentine and the shear stress on the cement layers. Endocrowns are not recommended in cases with no remaining buccal and lingual coronal walls, in which other restorative treatment options should be considered. The use of ceramics with endocrowns could enhance their long term bonding efficiency and retention, while resin composite endocrowns present a lower risk of catastrophic failure, especially in cases with minimal remaining coronal tooth structure.

Chapter 6

General Discussion, Limitations, and Conclusions

6.1 General discussion

Restorative dentistry is considered one of the most critical phases of dental treatment (Strub et al., 2006). Advances in materials, techniques, and equipment have altered both the science and art of restorative dentistry, and future developments will continue the progress of this discipline. The new era of adhesive dentistry along with the introduction of all ceramic and hybrid crown materials with improved mechanical and aesthetic features (Van Meerbeek et al., 2001), directed the practice in modern conservative dentistry towards minimally invasive preparations with maximal conservation of dental tissues (Plotino et al., 2008, Angeletaki et al., 2016). Adhesive restorations demonstrated adequate biomechanical performance *in-vitro* and *in-vivo* (Plotino et al., 2008, Angeletaki et al., 2016, Moezizadeh and Mokhtari, 2011).

Endocrowns are introduced as an alternative, conservative treatment for restoring ETT due to their advantages in preserving the maximum tooth structure, reducing the need for additional retentive techniques, saving treatment time and cost as less procedural steps are required in comparison to the conventional post-core retained crowns (Bindl et al., 2005, Belleflamme et al., 2017).

The appropriate restorative technique and the type of restorative material applied are factors affecting the longevity of restored teeth (Ferrari et al., 2000). The quality and integrity of the remaining tooth structure must be preserved carefully in order to provide a solid base for restoration and enhancing the structural strength of the restored tooth (Assif et al., 2003, Linn and Messer, 1994, Johnson et al., 1976, Schwartz and Robbins, 2004, Dietschi et al., 2007, Slutzky-Goldberg et al., 2009). Hence, the success of a dental restoration is determined by several main factors including: resistance to fracture, the aesthetic value, marginal fit, internal adaptation, and the amount of remaining sound tooth structure (Hunter and Hunter, 1990, Felton et al., 1991).

Insufficient fracture strength of the tooth-restoration complex could lead to mechanical failures such as cracks or fractures of the tooth and restoration. This will cause negative financial and legal effects for both the patient and the dental practitioner. Moreover, replacement of restorations can be challenging and require further removal of tooth structure, hence causing biological consequences. Material properties and modulus of elasticity are important factors for fracture strength of restored teeth (Hassouneh et al., 2020, Bindl et al., 2003, Costa et al., 2014). Furthermore, the mechanical strength of restored teeth is also influenced by the amount and quality of the remaining tooth structure. Coronal tissue remnant is reported to have a significant effect on the biomechanical behavior of ETT restored with post retained crowns (Ma et al., 2009, Juloski et al., 2014a).

Accurate marginal and internal fit testing is also crucial for indirect restorations to avoid resin cement wear and plaque accumulation (Björn et al., 1970). The formation of gaps at restoration margins will expose resin cement to the oral environment which could contribute to cement dissolution and restoration adhesive failure (Jacobs and Windeler, 1991, White et al., 1994, Gu and Kern, 2003, Rossetti et al., 2008). Secondary caries induced by debris and food at the marginal gaps is another potential complication of increased marginal discrepancies (Jokstad, 2016). Moreover, restorations of in adequate fit will not be properly supported by the tooth structure, which could affect the retention and longevity of the restoration (Larson, 2012).

The durability and reliability testing of dental restorations in clinical trials could be very challenging, due to technical, standardisation, and ethical considerations. Therefore, *in-vitro* testing is commonly used to investigate different materials and techniques pre-clinically. Such pre-clinical evaluation of new restorative techniques, materials and their clinical durability is crucial to prevent both financial and biological consequences.

Therefore, the aim of this project was to perform pre-clinical, *in-vitro* testing, 3D imaging and computer simulation analysis to evaluate the reliability of endocrown restorations in restoring ET premolar teeth. Investigating and refining this restorative technique pre-clinically to ensure optimum performance as a conservative alternative to conventional post-core retained crowns is of utmost clinical significance. The main goals of these investigations are to predict the clinical performance of endocrowns and to provide guidelines for their use in clinical practice.

Natural teeth were used in this project for mechanical and fitting accuracy testing. Moreover, the finite element (FE) models were generated from a CT scan of a natural premolar tooth, ensuring more accurate clinical simulation and representation of the internal structure (Vasco et al., 2015). Despite the associated variabilities of natural teeth owing to the difficulty in standardising specimens, and differences in dimensions and physical properties of their hard tissue materials, natural teeth accurately resemble the impact of tooth structure preparation for adhesive bonding, consequences, and distribution of polymerisation shrinkage of the resin cement on the mechanical behaviour and fitting accuracy of restored teeth. As opposed to standardised artificial dies (Moore et al., 1985, Chan et al., 2005), natural teeth also allow reproduction of micro retentive features, hence an accurate measurement of their effects on the mechanical and fitting accuracy. Throughout this project, identical parameters, processes and machines were used in the entire workflow from teeth preparation, optical scanning, milling of the reconstructions, cementation, to standardised scanning and mechanical testing conditions in an effort to ensure maximum standardisation and reliable results. This was also done in a matter similar to what is applied in the clinical environment to ensure maximum clinical simulation.

Testing dental restorations to assess their mechanical strength for different indications is commonly conducted through *in-vitro* testing using the static load to fracture method. However, the clinical relevancy of such tests depending solely on static testing has been questioned, since fatigue is reported as one of the main causes behind clinical failure of dental restorations. Pure static loading studies could present high magnitudes of loading that are not representative of the clinical environment or teeth in function. (Kelly et al., 2012). However, *in-vitro* testing incorporating fatigue tests could better simulate the *in-vivo* environment and their results will present more translational meaning (Baldissara et al., 2010). This kind of pre-clinical *in-vitro* investigations helps rank the increasing potential of different restorative materials and procedures for certain clinical indications that require different mechanical and physical properties. A systematic review recommended that fatigue testing should be incorporated in future studies in order to achieve more clinically relevant results taking into account the ultimate strength of the material to be tested after fatigue (Özcan and Jonasch, 2018). Accordingly, the first part of this project (chapter 3) included a mechanical *in-vitro* study with an extensive thermal and mechanical fatigue testing of endocrown restored teeth under a controlled and standardised environment. Application of 600,000 loading cycles and a load range of 10 to 50N was conducted, which mimics 2.5 years of *in-vivo* function (Ramirez-Sebastia et al., 2013). Previous studies have reported that artificial aging simulation may result in a significantly lower load-to-failure under compressive testing when compared to cases not subjected to aging simulation (Winter et al., 2019, Borges et al., 2009).

The number of mechanical fatigue cycles ranging from minimum 100x to maximum 28×10^6 has been reported in the literature in an attempt to investigate fixed dental restorations (Özcan and Jonasch, 2018). Variations have also been reported in the magnitude of the load applied for fatigue testing in previous studies ranging from 0 to 300 N (Rosentritt et al., 2000, Rosentritt et al., 2008, Rosentritt et al., 2011). However, it should be noted that the highest magnitude of the load applied in a fatigue test should not exceed 50% of the ultimate strength of the material tested (Rosentritt et al., 2006, Rosentritt et al., 2008).

That being said, teeth in the oral environment are subjected to functional and para-functional forces that occur within the mouth, which could cause extremely complex structural responses in the tooth-restoration complex. Determination of resulting stresses can be achieved only with a proper stress-analysis techniques and sufficient information of the characteristics of the oral tissues and restorative materials. Finite element analysis (FEA) is a method that can analyse complex structures and calculate the stress distribution within these structures (Dartora et al., 2018). This technique can be useful in investigating different aspects related to endocrown restorations due to the enormous variability of the data received from *in-vitro* studies (Aktas et al., 2018, Altier et al., 2018, Biacchi and Basting, 2012). The advances in imaging techniques and the progress of structural FE modeling and meshing, resulted in more accurate and reliable biomechanical analysis of structures using FE analysis. In addition, the simplicity of the endocrown restoration design and the presence of only one cement layer compared to the complex multiple interfaces presented in the post crown restorations, makes the former more reliable for investigation using FEA simulation methods (Lin et al., 2013).

Therefore, conducting a computational finite element study in chapter 5 along with laboratory *in-vitro* mechanical testing, provided significant information on the mechanical performance of endocrown restored teeth, and assisted in better understanding and justification of the laboratory results, as demonstrated below. Such comprehensive mechanical testing is crucial to the clinician for selecting a design, material, and preparation technique to provide the best prognosis for longevity.

Results from the current project demonstrated that endocrowns may perform as well as post-crowns in restoring ET premolar teeth. Both reconstructions survived the extensive dynamic fatigue test and thermo-cycling. Despite the extensive fatigue testing and oblique static loading, the results were often higher than generally accepted chewing forces for the premolar region. The higher estimates of bite force in the premolar region were reportedly 520 N during function and 800 N during clinching (Bousdras et al., 2006, Hidaka et al., 1999).

Interestingly, the results showed a significant interaction effect between the reconstruction design (endocrown or post-crown) and the type of material used ($p<0.001$). The investigated CAD/CAM resin-based composite material resulted in highest load-to-failure among endocrowns, while monolithic translucent zirconia resulted in highest load-to-failure among post-crown reconstructions (Chapter 3: Table 11). Moreover, only post-core retained zirconia crowns reported similar load-to-failure values when compared to sound teeth, while other groups showed lower values. However, it was noted that monolithic zirconia resulted in the highest number of catastrophic failures in both reconstruction designs (Figure 38). The FE results showed that models of restored teeth transferred higher maximum principal stress in an apical direction towards root dentine indicating higher risk of catastrophic failure compared to sound teeth (Chapter 5: Figure 35, Figure 36). This supports our results from the *in-vitro* study in addition to other previous studies (Guo et al., 2016b).

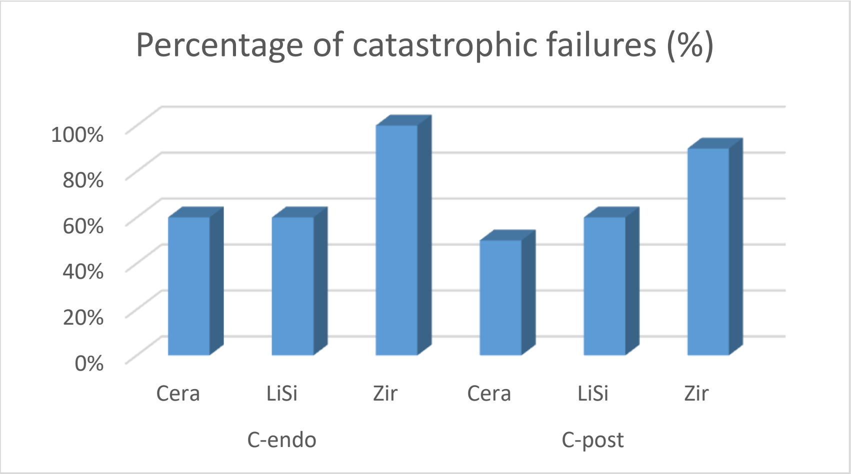


Figure 38 A bar chart presenting the percentage of catastrophic failures of the tested specimens in the mechanical *in-vitro* study (chapter 3). The chart illustrates that monolithic zirconia resulted in the highest number of catastrophic failures in both reconstruction designs.

The FEA study indicated lower transfer of stress to dentine structure and lower risk of catastrophic failure for models restored with resin composite endocrowns. Similarly, the mechanical *in-vitro* study demonstrated significantly higher load to failure values for resin composite endocrowns compared to other materials, in which this group exhibited mean load-to-failure exceeding 750 N indicating adequate biomechanical reliability even during (para) functional activities (Bousdras et al., 2006, Hidaka et al., 1999). This indicates that utilising restorative materials with lower elastic modulus like resin based composite blocks could improve the biomechanical behaviour of the endocrown restored tooth. CAD/CAM resin based composites are composed of polymer-matrices containing predominantly ceramic fillers and exhibit elastic modulus lower than ceramic materials (Gracis et al., 2015). Such materials have a higher tendency to bend under loading and distribute stresses more evenly leading to lower catastrophic failures (Mainjot et al., 2016). Previous *in-vitro* studies also demonstrated higher fracture strength and fewer catastrophic failures of CAD/CAM resin composite crowns when compared to lithium disilicate (LD) glass ceramic counterparts (El-Damanhoury et al., 2015, Taha et al., 2018a).

In the clinical intra-oral environment, restored teeth will be subjected to fatigue stress through repeated cyclic loading. This could lead to the development of microcracks, hence causing failure of the restored tooth (Ausiello et al., 2001).

These microcracks will form at areas of highest stress and lowest local strength. Studies reported that clinical fracture of restored teeth is usually initiated at these areas of high stress concentration such as the cervical area of dentine around the indirect restoration (Zarone et al., 2006). The current FEA study demonstrated that stresses were concentrated at the cervical area surrounding tooth-endocrown interface (Figure 39). Further, it has been noted that a higher mismatch of elastic moduli between tooth structure and reconstruction material would increase the chance for catastrophic failures involving root surface. This effect was evident in the *in-vitro* study too, as zirconia showed the highest percentage of catastrophic failures compared to LD glass ceramic and resin composites (p=0.011). The application of an oblique load on stiff zirconia resulted in stress concentration on the facial-cervical area of the root resulting in spall formation involving the CEJ and beyond (Figure 39).

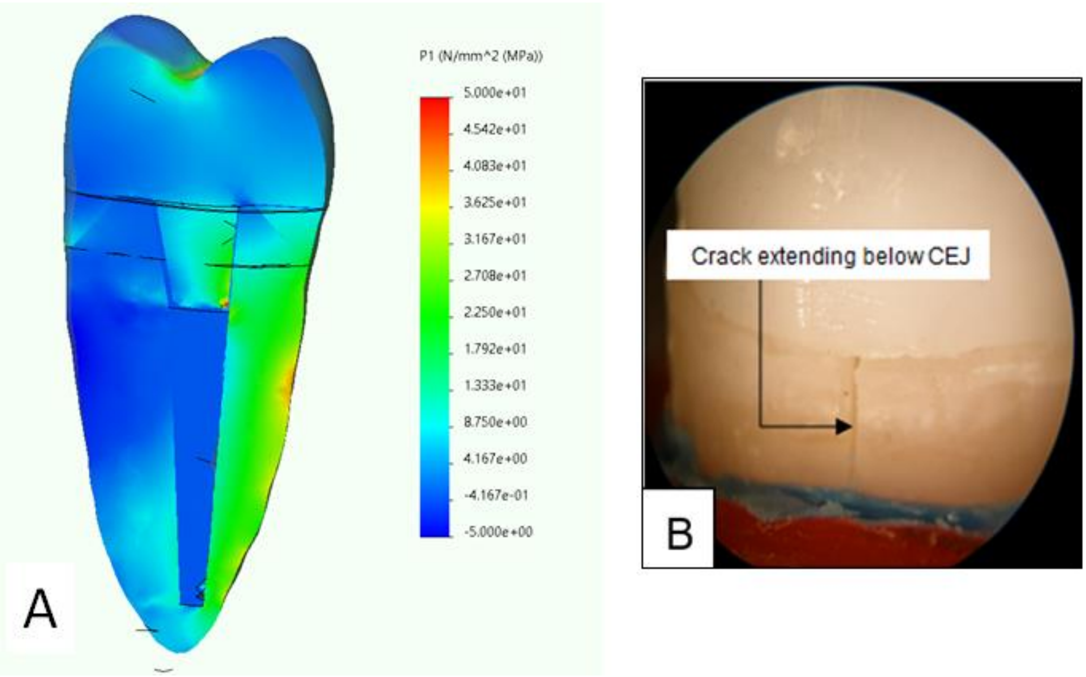


Figure 39 An image illustrating similar areas of high stress concentration and failure initiation in both FEA and *in-vitro* results. A: areas of high maximum principal stress in cross section of FE model presented in green, orange and red (cervical area of dentine around the endocrown restoration). B: Fracture Type IV failure in tooth restored with endocrown, showing a crack at tooth restoration interface and extending below CEJ.

On the other hand, despite the high compatibility between the elastic moduli of resin based composite endocrowns and dentine, and the lower risk of catastrophic failure reported in the FE analysis, 40% of resin composite endocrown specimens sustained catastrophic failures. This can be related to the high load-to-failure values (758N) compared to other groups, which allowed for greater transmission of force to the tooth structure. A similar effect was observed in another study as it has been reported that high fracture strength was associated with catastrophic fracture patterns regardless of the reconstruction design or material (Pedrollo Lise et al., 2017).

One major concern is the de-bonding of endocrown restorations as a result of stress concentration at the adhesive interface during function. The FEA study reported higher stress values at the cement layers and interfaces for resin endocrown models compared to ceramic models (Figure 40). This indicates that resin endocrowns are more prone to dislodgement failure at a later stage. Moreover, previous FEA studies reported that a restorative material with lower modulus of elasticity will result in lower bonding efficiency compared to materials with higher modulus of elasticity (Zhu et al., 2017).

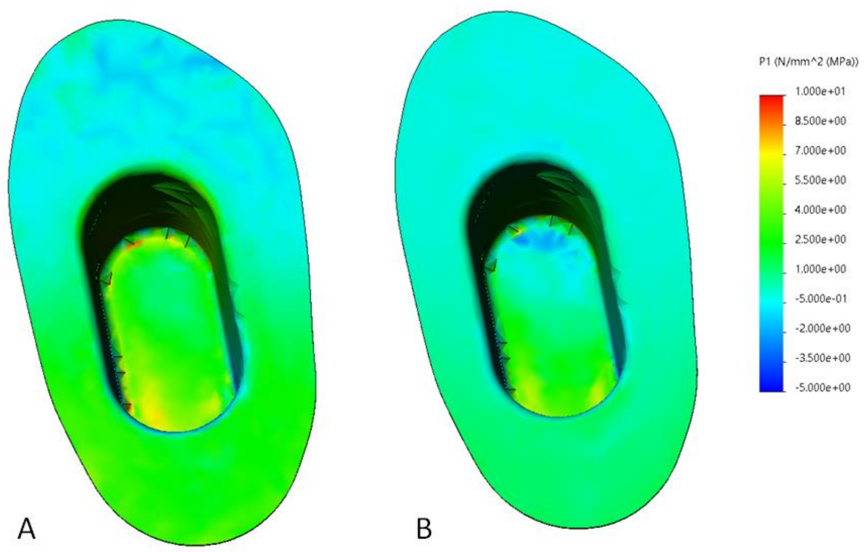


Figure 40 Maximum Principal Stress distribution (MPa) patterns in cement layers of (A): resin based composite endocrown model, (B): LD glass ceramic endocrown model under 200 N oblique load. The images illustrate higher stress concentration in resin based composite case presented by more distribution of green, orange and red colours.

That being said, none of the resin composite endocrown restorations exhibited de-bonding during the dynamic fatigue, thermo-cycling or fracture strength test in the *in-vitro* study. It should be noted that the difference in bonding efficiency between materials was less noticeable when sufficient amount of remaining tooth structure was preserved for restoration bonding and retention (Figure 41). Models with 2mm circumferential coronal dentine showed generally lower stress values throughout the cement layer, compared with partial remaining coronal dentine. This could explain the fact that no de-bonded cases were reported for both materials in the *in-vitro* study. In cases with sufficient coronal tissue, the endocrown margins are placed more coronal and the oblique loading is primarily resisted by natural tooth structure, thus demonstrating high load-to-failure and better bonding efficiency. However, when the palatal or buccal walls are missing, endocrowns could face premature de-bonding or fracture failure, in which other restorative options and treatments should be considered (Chapter 5: Table 19 & 20).

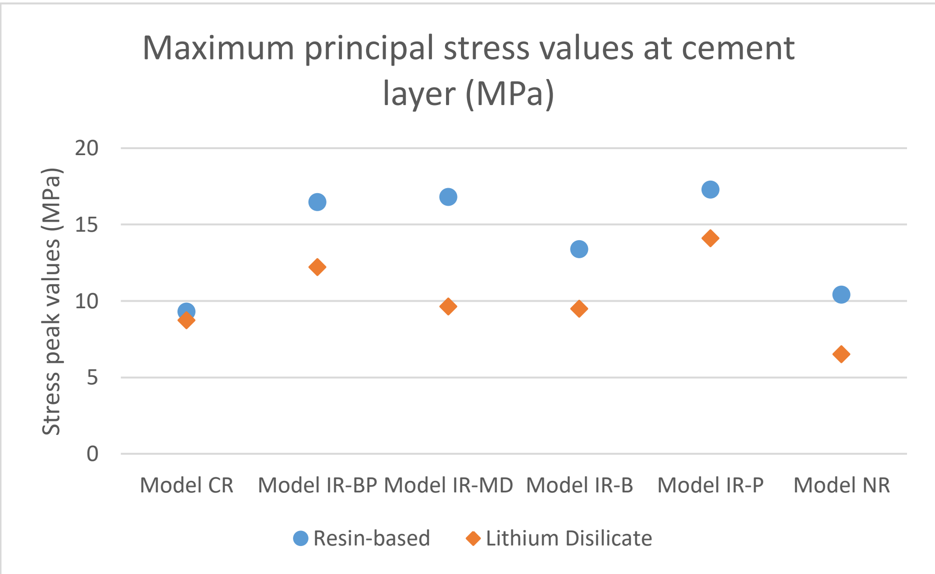


Figure 41 A line chart presenting the average of maximum principal stress high peaks at the cement layer of different FE models under 200 N oblique load (N/mm^2 (MPa)). The chart illustrates higher stress values at the cement layers for resin endocrown models compared to ceramic models however the difference was less noticeable when sufficient amount of remaining tooth structure was preserved (Model CR).

Another important concern with CAD/CAM resin based composite materials, is their high coefficient of thermal expansion. Studies reported that thermo-cycling of endocrowns fabricated from a CAD/CAM resin composite substrate (Lava™ Ultimate, 3M ESPE, USA), resulted in significantly higher microleakage in comparison to feldspathic and LD glass ceramic endocrowns (El-Damanhoury et al., 2015). Coefficient of thermal expansion is largely affected by the resin content, since resins are the expansile phase of the material. Thus, we expect that microleakage can be more significant with Cera as the resin matrix constitutes 29 % wt of the material (Gracis et al., 2015). Further *in-vitro* and clinical studies are required to elucidate the effects of different materials, designs, and luting cements on the microleakage of endocrown restored teeth.

Resin luting is known to significantly increase the mechanical reliability of indirect restorations, however several factors could affect its reliability (Guess et al., 2009). Marginal and internal adaptation may largely influence the reliability of the adhesive interface where cracks are frequently initiated (Zhang et al., 2009, Federlin et al., 2007). A thick cement layer coupled with poor internal fit yields large amount of polymerisation shrinkage stresses leading to premature cohesive or adhesive failures (Ilie et al., 2006, Federlin et al., 2007). This issue is particularly critical in endocrowns given the high ratio of bonded to unbonded surfaces. Accordingly, in chapter 4, micro-CT technology was used to assess the marginal and internal adaptation of endocrown restorations using different CAD/CAM materials.

Testing the fitting accuracy of indirect restorations is also as important as investigating its mechanical properties. It is a useful way to assess their biological, aesthetic, retentive efficiency and durability. The fitting accuracy of any indirect coronal reconstruction is crucial for the long-term clinical success (Felton et al., 1991). Different methodologies have been used in *in-vitro* studies to evaluate the marginal and internal adaptation of the indirect restorations (Mously et al., 2014, Yildirim et al., 2017, Contrepois et al., 2013). The use of optical microscopes, stereomicroscopes, profile projectors, and scanning electron microscopes has been reported (McLean, 1971, Yildirim et al., 2017, Zarauz et al., 2016). In the present project, micro-CT analysis was used, which is considered a non-destructive method that provides a high-resolution and accurate analysis of the axial, coronal, sagittal, and transverse sections. In addition, this technique allows for a 2D and 3D analysis of the samples, which gives a much wider range of information than conventional 2D methods. A recent literature review reported that the use of at least 50 measurements per specimen and the combination with micro-CT analysis should carry out more reliable results than other conventional methods (Nawafleh et al., 2013). Similarly, another systematic review pointed out that the current state of the literature does not allow for a detailed comparison of different restorative systems in terms of marginal fit and the use of micro-CT should be recommended (Contrepois et al., 2013).

In the current project, the selection of measurement reference points was based on the description from Holmes et al (Holmes et al., 1989), with a total of 96 points of measurement for each specimen. In addition, measurements were taken both before and after cementation, as studies showed that reporting measurements only after cementation did not allow for evaluation of the relative effect of cementation process and cement properties on the marginal and internal adaptation (Groten et al., 1997). This is a major advantage of using the micro-CT method, since most previous mentioned techniques can be destructive and will not allow for re-measuring of the same sample. In addition, the current study did not include any adjustments made on the internal surface of endocrown restorations before taking the measurement. Previous studies reported that such adjustments like grinding procedures were an important source of result distortion and should not be used in studies of marginal fit (Boening et al., 2000, Contrepois et al., 2013).

The current micro-CT results reported superior internal adaptation for LD glass ceramic materials, however no significant differences were observed in marginal discrepancy values among materials. In spite of reporting lower adaptation for resin composite endocrowns, its marginal and internal misfit values were within the clinically acceptable range (Chapter 4: Table 13 & 14). A marginal or internal opening of ≤120 μm has been deemed clinically acceptable by McLean and Von Fraunhofer who examined >1000 crowns' 5-year clinical performance (McLean, 1971).

Moreover, the lack of significant difference between pre- and post-bonding accuracy of fit indicates the low film thickness of the used resin cement and adhesive system. As per the manufacturer, the thickness of the adhesive and resin cement film thickness is collectively less than 8 μm as a result of the homogenously dispersed barium glass nanofillers within the resin matrix. This and the fact that no de-bonded cases were observed during mechanical testing, also help support the perfect bonding assumption in the FEA study or at least indicate the limited effect of this assumption on the accuracy of the FEA results.

Accordingly, the current results from the *in-vitro*, FEA, and micro-CT studies suggest that when sufficient amount of sound tooth structure is available to support the resin based composite endocrown, concerns regarding the high risk of adhesive bond failure with resin endocrowns could be limited. However, further studies utilising different types of resin based composite CAD/CAM systems and resin luting cements could be beneficial in supporting the current results.

In general, CAD/CAM resin composites have improved physical properties, wear resistance and colour stability when compared with direct resin composites owing to the high degree of conversion achieved *via* post-cure, heat and/or pressure polymerisation (Silva et al., 2017, Awada and Nathanson, 2015). Furthermore, CAD/CAM resin composites may outperform ceramic counterparts for the following reasons: (i) reduced time, cost and flaws associated with milling process, (ii) no post-milling sintering is required, (iii) ease of adjustment, finishing and polishing with no need to glaze, (iv) less antagonistic tooth wear, and (v) improved repairability and modification using direct composite resin (Silva et al., 2017, Awada and Nathanson, 2015). However, CAD/CAM resin composites exhibit lower wear resistance, inferior aesthetic properties, lower internal fitting accuracy, higher water sorption and plaque retention when compared to ceramics (Silva et al., 2017).

That being said, the newly developed LD glass ceramic used in the current *in-vitro* study may differ significantly from previously investigated materials. The ease of milling is the hallmark of this advent owing to the homogenous dispersion of LD micro-crystals within the glassy matrix. As per the manufacturer, the milled substrate exhibits very smooth surface finish and requires simple polishing which we have observed in this study (Figure 42). In addition, this material requires no post-milling sintering and thereby can be assumed to result in better marginal adaptation *via* elimination of margin distortion observed with post-milling sintering (Vogel et al., 1997). However, the current results showed no significant difference in marginal and internal fitting accuracy compared to the conventional milled LD glass-ceramic endocrowns (EMC) ($p \geq 0.123$) (Figure 43). This supports results from previous studies reporting that crystallisation process resulted in a negligible (0.2–0.3%) volumetric shrinkage that had no effect on the accuracy of fitted crown reconstructions (Wiedhahn, 2007). In addition, the significantly inferior internal fit of Cerasmart, a fully cured material that requires no post-milling processing may indicate that crystallisation/sintering may not be solely responsible for such disparity in the accuracy of fit.

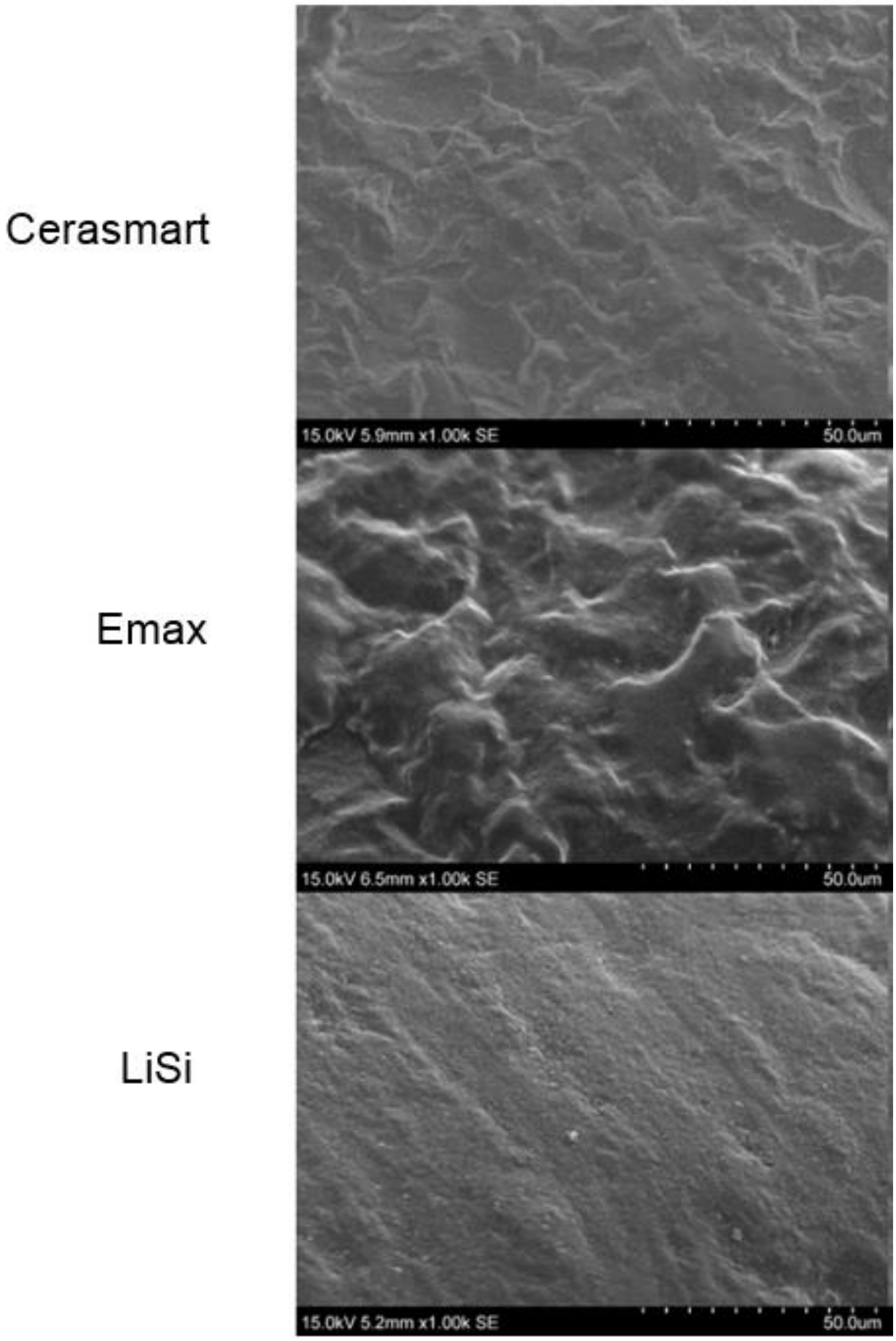


Figure 42 SEM micrographs (x1K) showing the surface topography of milled crowns from the three different materials used (CERASMART®270: GC Dental, Europe, IPS. e.max® CAD: Ivoclar Vivadent, Schaan, Initial® LiSi blocks: GC Dental, Europe). This illustrates the smooth surface finish of the new LD glass ceramic material (LiSi blocks), compared to other materials.

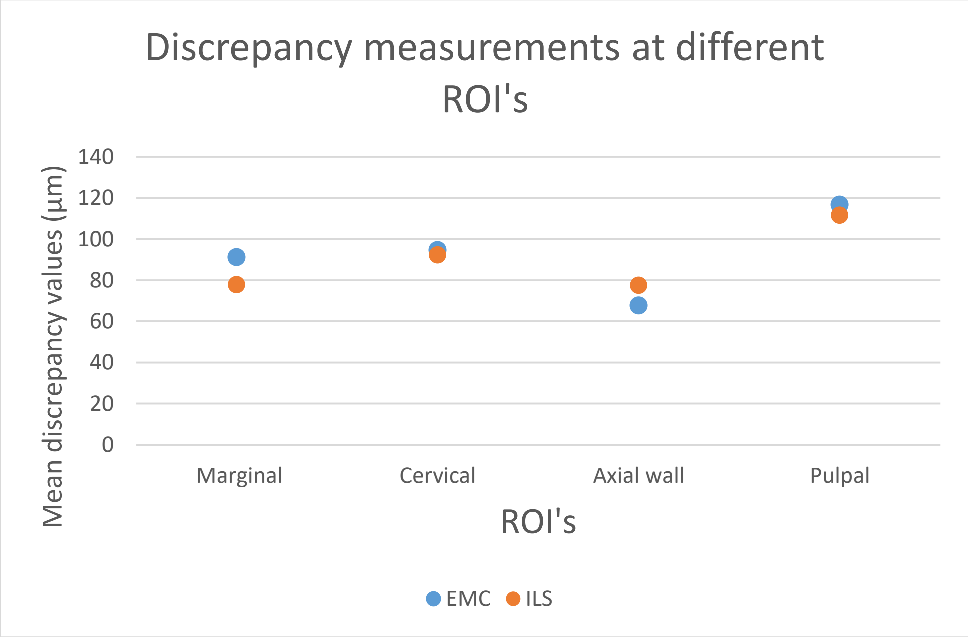


Figure 43 A line chart presenting mean values for discrepancy measurements according to ROI's of Emax and LiSi endocrowns (µm). This chart illustrates that discrepancy values were similar in both groups.

Some previous studies reported that crowns with better marginal and internal adaptation will show higher fracture strength values (Cho et al., 2002, May et al., 2012). However, our study reported significantly higher fracture strength for resin composite endocrowns compared to LD glass ceramic endocrowns, while the latter showed significantly better internal adaptation with no difference in their marginal misfit values. A previous study comparing different preparation designs also reported that the group of specimens showing better marginal adaptation reported lower fracture strength values (Cho et al., 2004). This indicates that a better crown adaptation does not necessarily enhance the fracture strength of the tooth-restoration complex. Furthermore, the current results did not report a significant correlation between the roughness of endocrown's fitting surfaces and the internal misfit values ($p \geq 0.082$). ILS showed the smoothest and most homogenous fitting surface, while CS reported the highest roughness measurements (Figure 44).

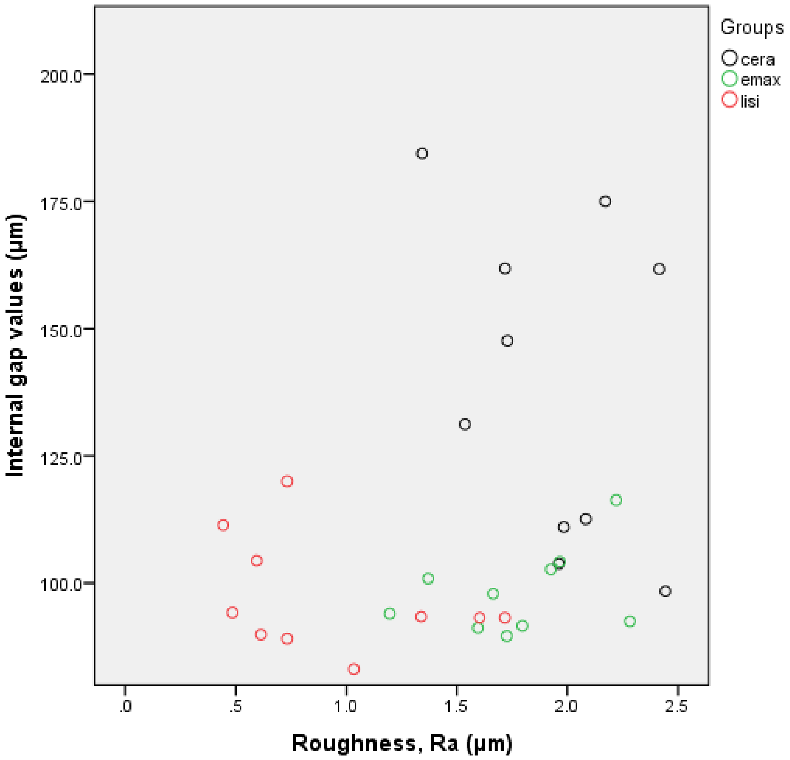


Figure 44 A scatter plot graph showing no correlation between the 2D internal misfit values (µm) and the fitting surface roughness (Ra (µm)) of endocrowns.

Studies that reported better machinability and adaptation of LD glass-ceramics attributed such findings to a low susceptibility to chipping and milling damage (Coldea et al., 2013a, Goujat et al., 2018, El Ghoul et al., 2019b). Contrarily, other studies reported superior adaptation of resin composite materials as a result of lower brittleness and better reproduction of fine surface details when compared to glass-ceramics (Awada and Nathanson, 2015, Rippe et al., 2017, de Paula Silveira et al., 2017).

It should be noted that several factors that derive from the manufacturing and fabrication process of each system could also affect the mechanical behaviour and fitting accuracy of restorations. Thus different techniques were deemed more or less sensitive (Sulaiman et al., 1997, Ural et al., 2010). The amount of direct human contribution in the manufacturing process of the restoration could play a role depending on the skill of the laboratory technician and the significance of his intervention (Zinelis, 2009). Another important factor is the number of steps involved in the process (Quintas et al., 2004, Ural et al., 2010, Sulaiman et al., 1997), since each additional step will increase the probability of error (Syrek et al., 2010). For instance, the use of a die spacer applied by a technician is indicated in non-CAD/CAM systems, in which the conventional In-Ceram slip-casting system has been described as singularly technique sensitive (Yeo et al., 2003). On the other hand, few steps are involved in the fabrication process of direct CAD/CAM systems (Ural et al., 2010, Syrek et al., 2010). The use of intraoral impressions will negate the indication of a die spacer in CAD/CAM systems. However, various optical impression systems might have different accuracy levels in data acquisition. Difference in software technologies and milling accuracy has also been reported (Alghazzawi et al., 2012, Iwai et al., 2008, Beuer et al., 2009). Moreover, the various experimental protocols used in different studies could also cause variations among the measured values.

Comparison of results from different studies investigating the mechanical properties, stress distribution analysis, characterisation, and fitting accuracy of restorations could be challenging due to the lack of standardisation between these studies. These results depend on different factors, including the type of restoration (endocrowns, crowns, post retained crowns, inlays, and onlays), the different materials examined, the fabrication method, the measurement techniques, the scanning and milling systems used, the size of the milling burs, the cement space, the mechanical testing parameters, and the experimental environment. These parameters should be standardised in dental *in-vitro* and FEA studies in order to obtain more comparable results. Whether such parameters could affect the fatigue, fracture resistance, stress distribution and adaptation of endocrown restored teeth needs further focus in future.

6.2 Limitations:

In-vitro preclinical investigations and FEA studies are a powerful tool in restorative dentistry and essential to ensure optimum performance in clinical practice. However, pre-clinical studies could exhibit some limitations in simulating several clinical factors that might influence restoration longevity. Teeth in the oral environment are subjected to saliva, bacteria, acidic fluids, parafunctional forces and other factors, in which all can have an effect on the restored tooth and its bonding durability. The complicated clinical environment cannot be properly simulated in FEA or *in-vitro* studies, hence further *in-vivo* studies are required to support such results and investigate the long-term clinical efficiency of endocrowns.

Another limitation of this project was the investigation of limited types of CAD/CAM systems and adhesive cements. Whether the results of this study can be transferred to other luting systems or to other types of dental CAD/CAM materials, needs to be investigated in further studies. However, it should be noted that previous research demonstrated comparable properties/performance of investigated materials when compared to counterparts produced by other manufacturers (Lawson et al., 2016).

Some simplifications and assumptions were applied in the FEA computational study due to the elaborate models investigated, the difficulty involved in simulating the mechanical properties and behaviour of the complex PDL structure, and the complex load and boundary conditions in the oral environment.

That being said, *in-vitro* and FE studies are often used to determine the tendency and difference among various factors instead of calculating the absolute value due to such unavoidable limitations. Thus, these limitations should not affect the ability of results in representing the tendency of biomechanical behaviour for endocrown restored teeth.

6.3 Conclusions:

The selection of a preparation and reconstruction design or material should not be based primarily on one parameter but rather on each treatment ability to provide the best mechanical, biological, and esthetic requirements. From a clinical point of view, endocrowns are less time-consuming, cost-effective, contain a single adhesive interface and are associated with minimal risk of iatrogenic damage or technical complications (Bindl et al., 2005, Belleflamme et al., 2017). The supra-gingival butt margins required for endocrown preparation are easy to prepare and record with conventional or optical impressions. Clinical assessment of the marginal fit, cement excess removal and maintenance of endocrowns are simpler compared to post-crown reconstructions.

In summary, this project supports endocrowns as an alternative approach to successfully restore endodontically treated premolars provided appropriate preparation, case selection, restorative material, and bonding protocols are utilised. When 2 mm circumferential coronal tooth structure is preserved, the fracture strength, stress distribution and adaptation of resin-based composite and LD glass ceramic endocrowns were found clinically acceptable. The following conclusions can be drawn from the current investigations:

- Both post-crown and endocrown reconstructions restoring endodontically treated premolar teeth were able to survive dynamic fatigue test and thermo-cycling simulating 2.5 years of clinical service.
- A significant interaction between reconstruction design and material type was observed, in which the resin-based composite material resulted in highest load-to-failure among endocrowns, while monolithic translucent zirconia showed the highest load-to-failure among post-crown reconstructions.
- Teeth restored with post-core and zirconia crowns exhibited load-to-failure values close to intact teeth (control group), however monolithic translucent zirconia resulted in the highest number of catastrophic failures in both post-crown and endocrown restored teeth. Hence, zirconia endocrowns should be avoided with premolar teeth owing to the low fracture resistance and high risk of catastrophic failures.

- The investigated LD glass ceramic CAD/CAM material demonstrated comparable load-to-failure in both post-crown and endocrown groups.
- A 2mm high circumferential remaining coronal tooth structure will reduce stress concentration on dentine and enhance the cement bonding efficiency.
- Endocrowns are not recommended in cases with no remaining buccal and lingual coronal walls, in which other restorative treatment options should be considered.
- The use of ceramics with endocrowns could enhance their long term bonding efficiency and retention, while resin composite endocrowns present a lower risk of catastrophic failure, especially in cases with minimal remaining coronal tooth structure.
- LD glass ceramic materials showed superior internal adaptation compared to resin based composite material, however all CAD/CAM systems tested for endocrown fabrication exhibited clinically acceptable marginal and internal misfits.
- The machinable, fully crystallised LD glass ceramic exhibited the smoothest and most homogenous endocrown fitting surface’s roughness profile, however no correlation was found between 2D internal misfit and the surface roughness profile of endocrown fitting surfaces.

Chapter 7

Future Work:

Endocrown restorations would require further preclinical and clinical investigations, this provides a large scope of future work to test the following:

- Investigate endocrowns using different marginal preparation designs:

Regarding the margin design in endocrown preparation, some authors (Fages and Bennasar, 2013) used a butt margin as described earlier by Bindl and Mormmann (Bindl and Mormann, 1999), while others used a shoulder margin with axial reduction as in all ceramic conventional crowns. Since butt joint designs are prepared parallel to the occlusal plane, they are expected to resist the compressive stresses by providing a stable surface. On the other hand, adding short axial walls with shoulder finish line, can moderate the load on the pulpal floor, since shear stresses can be counteracted through the walls with better load distribution through the walls and margins (Taha et al., 2018b). Although numerous studies have investigated the effect of ferrule preparation on the mechanical behavior of endodontically treated teeth restored with various post and core systems, very few studies investigated its effect on teeth restored with endocrowns. Therefore, there is no sufficient scientific evidence on the importance of different margin preparation designs for endocrown restorations.

- Evaluate the effect of different adhesive systems on the bonding durability and overall mechanical and biological properties of endocrown restored teeth:

Resin luting is known to significantly increase the mechanical reliability of indirect restorations, however several factors could affect its reliability (Guess et al., 2009). The unique preparation design of endocrowns could illustrate further concerns regarding the efficiency of different luting systems. This can be related to the different surface area available for bonding as well as limited penetration ability of the curing light to polymerise resin cement in the retention cavity. Although the current investigations reported optimum resin bonding efficiency during cyclic and static loading, more studies are required to investigate the bonding efficiency of different cement groups in different clinical situations.

- Investigate the mechanical influence of different preparation designs and depth of the endocrown core or central retainer:

The preparation depth of the central retentive cavity, or the length of the endo core is another controversial issue in preparing teeth for endocrowns. Further unnecessary preparation of sound tooth structure could be avoided by using a shallow central cavity preparation, and hence reducing the chance of root perforation and excessive tooth weakening. On the other hand, preparing a deeper central retentive cavity could enhance the adhesive retention by providing a greater surface area for retention and might result in better distribution of masticatory forces to the root (Mörmann et al., 1998). Until now there is insufficient data on the preferred endo-core preparation depth with various results reported (Hayes et al., 2017, Carvalho et al., 2016, Lise et al., 2017), hence further studies are required to demonstrate its significance over the effectiveness of endocrowns.

- Incorporation of newly developed CAD/CAM materials in the fabrication of endocrowns and evaluate its aesthetic, mechanical, and biological effect:

Studies have found that the type of materials used in restoring ETT can significantly affect the fracture strength of these teeth and hence affect the outcome of treatment. (Dietschi et al., 2008, Heydecke and Peters, 2002, Rocca et al., 2016b). With the increased range of materials that are currently available to use, in addition to the great developments in industry and digital technology, especially the CAD/CAM technology, the decision to choose the right material for different clinical situations became more challenging and a continuous area of research in restorative dentistry.

- To investigate the coronal seal efficiency and microleakage with different endocrown preparation designs including different central retainer depth preparations:

The outcome of endodontic treatment and tooth restoration is affected by several factors; however microbial contamination is the main cause of endodontic failure. Due to the unique preparation design of endocrowns, and the fact that the restoration is extended inside the pulp chamber, microbial leakage is a critical factor that should be thoroughly investigated under different clinical situations. The effect of using intra-coronal barrier, the length of endo-core depth, and the type of cement material are all factors that can have an effect on endocrown coronal seal efficiency. However until now there is no clear scientific evidence on this topic.

- To evaluate the aesthetic and biological effects of the endocrown supragingival margins:

One of the main advantages of endocrown restorations are their conservative supra-gingival margins. Supra-gingival margins overcomes the complications and difficulties associated with gingival and sub gingival margins such as the difficulty in cavity preparation, impression taking, and adhesive cementation under isolation. On the other hand, supra-gingival margins could face esthetical challenges if inappropriate ceramic shades were applied. In addition such margins should be plain, smooth and accessible for proper oral hygiene to be achieved. The long term clinical outcome and patient esthetic satisfaction with endocrowns are important factors that should be investigated.

- To translate the experimental investigations for clinical use and conduct long term clinical trials to evaluate the clinical performance of endocrown restorations compared to other conventional restorative techniques:

Although preclinical studies are essential for all aspects of restorative dentistry research, pre-clinical studies could exhibit some limitations in simulating several clinical factors that might influence restoration longevity. Teeth in the oral environment are subjected to saliva, bacteria, acidic fluids, parafunctional forces and other factors, in which all can have an effect on the restored tooth and its bonding durability. The complicated clinical environment cannot be properly simulated in FEA or *in-vitro* studies, hence further *in-vivo* studies are required to support such results and investigate the long term clinical efficiency of endocrowns.

Chapter 8

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Chapter 9
Appendices

Appendix A
Load-to-failure data analysis

Descriptive analysis and normality test for load-to-failure (N) values

Descriptives

	Group			Statistic	Std. Error
Load (N)	Intact teeth	Mean		947.40	70.517
		95% Confidence Interval for Mean	Lower Bound	787.88	
			Upper Bound	1106.92	
		5% Trimmed Mean		953.39	
		Median		949.00	
		Variance		49727.156	
		Std. Deviation		222.996	
		Minimum		560	
		Maximum		1227	
		Range		667	
		Interquartile Range		344	
		Skewness		-.568	.687
		Kurtosis		-.355	1.334

E-Cera	Mean		758.10	33.273
	95% Confidence Interval for Mean	Lower Bound	682.83	
		Upper Bound	833.37	
	5% Trimmed Mean		760.94	
	Median		774.00	
	Variance		11070.989	
	Std. Deviation		105.219	
	Minimum		569	
	Maximum		896	
	Range		327	
	Interquartile Range		189	
	Skewness		-.409	.687
	Kurtosis		-.593	1.334
E-LiSi	Mean		547.40	44.761
	95% Confidence Interval for Mean	Lower Bound	446.14	
		Upper Bound	648.66	
	5% Trimmed Mean		540.83	
	Median		527.50	
	Variance		20035.600	
	Std. Deviation		141.547	

	Minimum		378	
	Maximum		835	
	Range		457	
	Interquartile Range		223	
	Skewness		.839	.687
	Kurtosis		.354	1.334
E-Zir	Mean		460.00	35.425
	95% Confidence Interval for Mean	Lower Bound	379.86	
		Upper Bound	540.14	
	5% Trimmed Mean		457.00	
	Median		456.00	
	Variance		12549.333	
	Std. Deviation		112.024	
	Minimum		323	
	Maximum		651	
	Range		328	
	Interquartile Range		173	
	Skewness		.358	.687
	Kurtosis		-.988	1.334
GF-Cera	Mean		477.00	42.518
	95% Confidence Interval for Mean	Lower Bound	380.82	

		Upper Bound	573.18	
	5% Trimmed Mean		470.44	
	Median		440.00	
	Variance		18077.778	
	Std. Deviation		134.454	
	Minimum		304	
	Maximum		768	
	Range		464	
	Interquartile Range		164	
	Skewness		1.100	.687
	Kurtosis		1.350	1.334
GF-LiSi	Mean		534.10	37.647
	95% Confidence Interval for Mean	Lower Bound	448.94	
		Upper Bound	619.26	
	5% Trimmed Mean		525.50	
	Median		485.50	
	Variance		14172.989	
	Std. Deviation		119.050	
	Minimum		421	
	Maximum		802	
	Range		381	

		Interquartile Range		162	
		Skewness		1.485	.687
		Kurtosis		1.871	1.334
	GF-Zir	Mean		815.60	27.689
		95% Confidence Interval for Mean	Lower Bound	752.96	
			Upper Bound	878.24	
		5% Trimmed Mean		814.94	
		Median		820.00	
		Variance		7666.711	
		Std. Deviation		87.560	
		Minimum		675	
		Maximum		968	
		Range		293	
		Interquartile Range		137	
		Skewness		.101	.687
		Kurtosis		-.392	1.334

Tests of Normality

		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Group	Statistic	df	Sig.	Statistic	df	Sig.
Load (N)	Intact teeth	.204	10	.200*	.918	10	.337
	E-Cera	.119	10	.200*	.962	10	.809

E-LiSi	.128	10	.200*	.943	10	.583
E-Zir	.157	10	.200*	.938	10	.535
GF-Cera	.177	10	.200*	.919	10	.352
GF-LiSi	.238	10	.114	.844	10	.049
GF-Zir	.130	10	.200*	.984	10	.984

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Two-way analysis of variance (two-way ANOVA) to test the factors 'restoration design' and 'type of material'

Tests of Between-Subjects Effects

Dependent Variable: Load

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	2175288.486[a]	6	362548.081	19.038	.000	.645
Intercept	30107169.000	1	30107169.000	1581.015	.000	.962
Design	6242.400	1	6242.400	.328	.569	.005
Material	104846.700	2	52423.350	2.753	.071	.080
Design * Material	1021984.900	2	510992.450	26.834	.000	.460
Error	1199705.000	63	19042.937			
Total	32814948.000	70				
Corrected Total	3374993.486	69				

Post-hoc Tukey multiple comparisons to compare between different experimental groups

Pairwise Comparisons

Dependent Variable: Load

Design	(I) Material	(J) Material	Mean Difference (I-J)	Std. Error	Sig.[d]	95% Confidence Interval for Difference[d] Lower Bound	Upper Bound
control sound tooth	control sound tooth	Cera	.[a]	.	.	.	.
		LiSi	.[a]	.	.	.	.
		Zir	.[a]	.	.	.	.
	Cera	control sound tooth	.[b]	.	.	.	.
		LiSi	.[a,b]	.	.	.	.
		Zir	.[a,b]	.	.	.	.
	LiSi	control sound tooth	.[b]	.	.	.	.
		Cera	.[a,b]	.	.	.	.
		Zir	.[a,b]	.	.	.	.
	Zir	control sound tooth	.[b]	.	.	.	.

		Cera	.[a,b]	.	.	.	.
		LiSi	.[a,b]	.	.	.	.
Endocrown	control sound tooth	Cera	.[b]	.	.	.	.
		LiSi	.[b]	.	.	.	.
		Zir	.[b]	.	.	.	.
	Cera	control sound tooth	.[a]	.	.	.	.
		LiSi	210.700*	61.714	.001	87.375	334.025
		Zir	298.100*	61.714	.000	174.775	421.425
	LiSi	control sound tooth	.[a]	.	.	.	.
		Cera	-210.700*	61.714	.001	-334.025	-87.375
		Zir	87.400	61.714	.162	-35.925	210.725
	Zir	control sound tooth	.[a]	.	.	.	.
		Cera	-298.100*	61.714	.000	-421.425	-174.775

		LiSi	-87.400	61.714	.162	-210.725	35.925
Post-Crown	control sound tooth	Cera	.[b]	.	.	.	.
		LiSi	.[b]	.	.	.	.
		Zir	.[b]	.	.	.	.
	Cera	control sound tooth	.[a]	.	.	.	.
		LiSi	-57.100	61.714	.358	-180.425	66.225
		Zir	-338.600*	61.714	.000	-461.925	-215.275
	LiSi	control sound tooth	.[a]	.	.	.	.
		Cera	57.100	61.714	.358	-66.225	180.425
		Zir	-281.500*	61.714	.000	-404.825	-158.175
	Zir	control sound tooth	.[a]	.	.	.	.
		Cera	338.600*	61.714	.000	215.275	461.925

		LiSi	281.500*	61.714	.000	158.175	404.825

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. The level combination of factors in (J) is not observed.

b. The level combination of factors in (I) is not observed.

d. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Pairwise Comparisons

Dependent Variable: Load

Material	(I) Design	(J) Design	Mean Difference (I-J)	Std. Error	Sig.[d]	95% Confidence Interval for Difference[d] Lower Bound	Upper Bound
control sound tooth	control sound tooth	Endocrown	.[a]	.	.	.	.
		Post-Crown	.[a]	.	.	.	.
	Endocrown	control sound tooth	.[b]	.	.	.	.
		Post-Crown	.[a,b]	.	.	.	.

	Post-Crown	control sound tooth	.[b]	.	.	.	.
		Endocrown	.[a,b]	.	.	.	.
Cera	control sound tooth	Endocrown	.[b]	.	.	.	.
		Post-Crown	.[b]	.	.	.	.
	Endocrown	control sound tooth	.[a]	.	.	.	.
		Post-Crown	281.100*	61.714	.000	157.775	404.425
	Post-Crown	control sound tooth	.[a]	.	.	.	.
		Endocrown	-281.100*	61.714	.000	-404.425	-157.775
LiSi	control sound tooth	Endocrown	.[b]	.	.	.	.
		Post-Crown	.[b]	.	.	.	.
	Endocrown	control sound tooth	.[a]	.	.	.	.
		Post-Crown	13.300	61.714	.830	-110.025	136.625
	Post-Crown	control sound tooth	.[a]	.	.	.	.
		Endocrown	-13.300	61.714	.830	-136.625	110.025
Zir	control sound tooth	Endocrown	.[b]	.	.	.	.
		Post-Crown	.[b]	.	.	.	.
	Endocrown	control sound tooth	.[a]	.	.	.	.
		Post-Crown	-355.600*	61.714	.000	-478.925	-232.275
	Post-Crown	control sound tooth	.[a]	.	.	.	.
		Endocrown	355.600*	61.714	.000	232.275	478.925

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. The level combination of factors in (J) is not observed.

b. The level combination of factors in (I) is not observed.

d. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Multiple Comparisons

Dependent Variable: Load

Tukey HSD

(I) Design	(J) Design	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
control sound tooth	Endocrown	358.9000*	50.38907	.000	237.9498	479.8502
	Post-Crown	338.5000*	50.38907	.000	217.5498	459.4502
Endocrown	control sound tooth	-358.9000*	50.38907	.000	-479.8502	-237.9498
	Post-Crown	-20.4000	35.63045	.835	-105.9247	65.1247
Post-Crown	control sound tooth	-338.5000*	50.38907	.000	-459.4502	-217.5498
	Endocrown	20.4000	35.63045	.835	-65.1247	105.9247

Based on observed means.

The error term is Mean Square(Error) = 19042.937.

*. The mean difference is significant at the .05 level.

Multiple Comparisons

Dependent Variable: Load

Tukey HSD

(I) Material	(J) Material	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
control sound tooth	Cera	329.8500*	53.44568	.000	188.8094	470.8906
	LiSi	406.6500*	53.44568	.000	265.6094	547.6906
	Zir	309.6000*	53.44568	.000	168.5594	450.6406
Cera	control sound tooth	-329.8500*	53.44568	.000	-470.8906	-188.8094
	LiSi	76.8000	43.63821	.302	-38.3592	191.9592
	Zir	-20.2500	43.63821	.967	-135.4092	94.9092
LiSi	control sound tooth	-406.6500*	53.44568	.000	-547.6906	-265.6094
	Cera	-76.8000	43.63821	.302	-191.9592	38.3592
	Zir	-97.0500	43.63821	.128	-212.2092	18.1092
Zir	control sound tooth	-309.6000*	53.44568	.000	-450.6406	-168.5594
	Cera	20.2500	43.63821	.967	-94.9092	135.4092
	LiSi	97.0500	43.63821	.128	-18.1092	212.2092

Based on observed means.

The error term is Mean Square (Error) = 19042.937.

*. The mean difference is significant at the .05 level.

Chi-square test to compare endocrown and post-crown groups in terms of failure modes

Fracture Pattern * Group Cross tabulation

Count

		Group		Total
		Endocrown	Crown	
Fracture Pattern	repairable	8	10	18
	unrepairable	22	20	42
Total		30	30	60

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	.317[a]	1	.573		
Continuity Correction[b]	.079	1	.778		
Likelihood Ratio	.318	1	.573		
Fisher's Exact Test				.779	.389
Linear-by-Linear Association	.312	1	.576		
N of Valid Cases	60				

a. 0 cells (0.0%) have expected count less than 5. The minimum expected count is 9.00.

b. Computed only for a 2x2 table

Appendix B

Marginal and Internal Data Analysis

Descriptive analysis and normality test

Descriptives (2D marginal and internal discrepancies of different ROI's according to the different materials tested)

	V1				Statistic	Std. Error
Absolute marginal discrepancy	Cera	Mean			.12550000	.010733903
		95% Confidence Interval for Mean	Lower Bound		.10121823	
			Upper Bound		.14978177	
		5% Trimmed Mean			.12436111	
		Median			.12150000	
		Variance			.001	
		Std. Deviation			.033943581	
		Minimum			.086000	
		Maximum			.185500	
		Range			.099500	
		Interquartile Range			.049000	
		Skewness			.858	.687
		Kurtosis			-.121	1.334
	Emax	Mean			.11970000	.004804627

		95% Confidence Interval for Mean	Lower Bound	.10883118	
			Upper Bound	.13056882	
		5% Trimmed Mean		.12005556	
		Median		.11650000	
		Variance		.000	
		Std. Deviation		.015193566	
		Minimum		.094000	
		Maximum		.139000	
		Range		.045000	
		Interquartile Range		.027000	
		Skewness		-.124	.687
		Kurtosis		-.987	1.334
	LiSi	Mean		.10495000	.007592193
		95% Confidence Interval for Mean	Lower Bound	.08777527	
			Upper Bound	.12212473	
		5% Trimmed Mean		.10558333	
		Median		.10625000	
		Variance		.001	
		Std. Deviation		.024008621	
		Minimum		.065500	
		Maximum		.133000	
		Range		.067500	

		Interquartile Range		.043625	
		Skewness		-.295	.687
		Kurtosis		-1.472	1.334
Marginal discrepancy	Cera	Mean		.05940000	.003032967
		95% Confidence Interval for Mean	Lower Bound	.05253895	
			Upper Bound	.06626105	
		5% Trimmed Mean		.05950000	
		Median		.06275000	
		Variance		.000	
		Std. Deviation		.009591084	
		Minimum		.045000	
		Maximum		.072000	
		Range		.027000	
		Interquartile Range		.018625	
		Skewness		-.408	.687
		Kurtosis		-1.429	1.334
	Emax	Mean		.06300000	.004917655
		95% Confidence Interval for Mean	Lower Bound	.05187549	
			Upper Bound	.07412451	
		5% Trimmed Mean		.06327778	
		Median		.06025000	
		Variance		.000	

		Std. Deviation		.015550991	
		Minimum		.037000	
		Maximum		.084000	
		Range		.047000	
		Interquartile Range		.029125	
		Skewness		.097	.687
		Kurtosis		-.741	1.334
	LiSi	Mean		.05075000	.003895332
		95% Confidence Interval for Mean	Lower Bound	.04193815	
			Upper Bound	.05956185	
		5% Trimmed Mean		.05063889	
		Median		.04800000	
		Variance		.000	
		Std. Deviation		.012318121	
		Minimum		.035000	
		Maximum		.068500	
		Range		.033500	
		Interquartile Range		.022125	
		Skewness		.245	.687
		Kurtosis		-1.677	1.334
Cervical seat	Cera	Mean		.15205000	.019250606
		95% Confidence Interval for Mean	Lower Bound	.10850210	
			Upper Bound	.19559790	

		5% Trimmed Mean		.15300000	
		Median		.13900000	
		Variance		.004	
		Std. Deviation		.060875761	
		Minimum		.065000	
		Maximum		.222000	
		Range		.157000	
		Interquartile Range		.121625	
		Skewness		.052	.687
		Kurtosis		-1.837	1.334
	Emax	Mean		.11380000	.006320689
		95% Confidence Interval for Mean	Lower Bound	.09950161	
			Upper Bound	.12809839	
		5% Trimmed Mean		.11463889	
		Median		.11350000	
		Variance		.000	
		Std. Deviation		.019987774	
		Minimum		.076500	
		Maximum		.136000	
		Range		.059500	
		Interquartile Range		.033625	
		Skewness		-.593	.687
		Kurtosis		-.426	1.334
	LiSi	Mean		.09810000	.007147571

	95% Confidence Interval for Mean	Lower Bound	.08193107	
		Upper Bound	.11426893	
	5% Trimmed Mean		.09805556	
	Median		.09750000	
	Variance		.001	
	Std. Deviation		.022602606	
	Minimum		.062000	
	Maximum		.135000	
	Range		.073000	
	Interquartile Range		.031375	
	Skewness		-.242	.687
	Kurtosis		-.238	1.334
Cervico-axial angle Cera	Mean		.10220000	.010062085
	95% Confidence Interval for Mean	Lower Bound	.07943798	
		Upper Bound	.12496202	
	5% Trimmed Mean		.10177778	
	Median		.10200000	
	Variance		.001	
	Std. Deviation		.031819107	
	Minimum		.062500	
	Maximum		.149500	
	Range		.087000	
	Interquartile Range		.066875	

		Skewness		.074	.687
		Kurtosis		-1.443	1.334
	Emax	Mean		.07545000	.003948593
		95% Confidence Interval for Mean	Lower Bound	.06651766	
			Upper Bound	.08438234	
		5% Trimmed Mean		.07516667	
		Median		.07475000	
		Variance		.000	
		Std. Deviation		.012486548	
		Minimum		.054500	
		Maximum		.101500	
		Range		.047000	
		Interquartile Range		.013875	
		Skewness		.540	.687
		Kurtosis		1.702	1.334
	LiSi	Mean		.08680000	.006087419
		95% Confidence Interval for Mean	Lower Bound	.07302930	
			Upper Bound	.10057070	
		5% Trimmed Mean		.08572222	
		Median		.08000000	
		Variance		.000	
		Std. Deviation		.019250108	
		Minimum		.066500	

		Maximum		.126500	
		Range		.060000	
		Interquartile Range		.031000	
		Skewness		1.121	.687
		Kurtosis		.459	1.334
Axial wall	Cera	Mean		.12485000	.009101602
		95% Confidence Interval for Mean	Lower Bound	.10426074	
			Upper Bound	.14543926	
		5% Trimmed Mean		.12383333	
		Median		.12175000	
		Variance		.001	
		Std. Deviation		.028781794	
		Minimum		.090500	
		Maximum		.177500	
		Range		.087000	
		Interquartile Range		.044750	
		Skewness		.682	.687
		Kurtosis		-.312	1.334
	Emax	Mean		.06775000	.007523759
		95% Confidence Interval for Mean	Lower Bound	.05073008	
			Upper Bound	.08476992	
		5% Trimmed Mean		.06561111	
		Median		.06175000	

		Variance		.001	
		Std. Deviation		.023792214	
		Minimum		.045500	
		Maximum		.128500	
		Range		.083000	
		Interquartile Range		.014500	
		Skewness		2.191	.687
		Kurtosis		5.242	1.334
	LiSi	Mean		.07755000	.008011953
		95% Confidence Interval for Mean	Lower Bound	.05942570	
			Upper Bound	.09567430	
		5% Trimmed Mean		.07552778	
		Median		.07250000	
		Variance		.001	
		Std. Deviation		.025336020	
		Minimum		.053500	
		Maximum		.138000	
		Range		.084500	
		Interquartile Range		.027375	
		Skewness		1.743	.687
		Kurtosis		3.246	1.334
Pulpal angle	Cera	Mean		.15745000	.014509662
		95% Confidence Interval for Mean	Lower Bound	.12462687	

		Upper Bound	.19027313	
	5% Trimmed Mean		.15561111	
	Median		.14325000	
	Variance		.002	
	Std. Deviation		.045883579	
	Minimum		.092000	
	Maximum		.256000	
	Range		.164000	
	Interquartile Range		.053375	
	Skewness		1.011	.687
	Kurtosis		1.506	1.334
Emax	Mean		.11530000	.003344315
	95% Confidence Interval for Mean	Lower Bound	.10773463	
		Upper Bound	.12286537	
	5% Trimmed Mean		.11588889	
	Median		.11625000	
	Variance		.000	
	Std. Deviation		.010575653	
	Minimum		.092500	
	Maximum		.127500	
	Range		.035000	
	Interquartile Range		.013750	
	Skewness		-1.135	.687

		Kurtosis		1.255	1.334
	LiSi	Mean		.10905000	.003652587
		95% Confidence Interval for Mean	Lower Bound	.10078728	
			Upper Bound	.11731272	
		5% Trimmed Mean		.10891667	
		Median		.10975000	
		Variance		.000	
		Std. Deviation		.011550493	
		Minimum		.091500	
		Maximum		.129000	
		Range		.037500	
		Interquartile Range		.017625	
		Skewness		.211	.687
		Kurtosis		-.434	1.334
Pulpal floor	Cera	Mean		.15720000	.011438046
		95% Confidence Interval for Mean	Lower Bound	.13132534	
			Upper Bound	.18307466	
		5% Trimmed Mean		.15761111	
		Median		.16850000	
		Variance		.001	
		Std. Deviation		.036170276	
		Minimum		.106000	
		Maximum		.201000	

	Range		.095000	
	Interquartile Range		.071000	
	Skewness		-.319	.687
	Kurtosis		-1.811	1.334
Emax	Mean		.11815000	.008164643
	95% Confidence Interval for Mean	Lower Bound	.09968030	
		Upper Bound	.13661970	
	5% Trimmed Mean		.11777778	
	Median		.10850000	
	Variance		.001	
	Std. Deviation		.025818867	
	Minimum		.091000	
	Maximum		.152000	
	Range		.061000	
	Interquartile Range		.052875	
	Skewness		.342	.687
	Kurtosis		-2.022	1.334
LiSi	Mean		.11445000	.002925415
	95% Confidence Interval for Mean	Lower Bound	.10783225	
		Upper Bound	.12106775	
	5% Trimmed Mean		.11494444	
	Median		.11500000	
	Variance		.000	

		Std. Deviation		.009250976	
		Minimum		.095000	
		Maximum		.125000	
		Range		.030000	
		Interquartile Range		.012625	
		Skewness		-.988	.687
		Kurtosis		.801	1.334
Marginal	Cera	Mean		.09245000	.005760835
		95% Confidence Interval for Mean	Lower Bound	.07941809	
			Upper Bound	.10548191	
		5% Trimmed Mean		.09204167	
		Median		.09300000	
		Variance		.000	
		Std. Deviation		.018217360	
		Minimum		.067000	
		Maximum		.125250	
		Range		.058250	
		Interquartile Range		.025813	
		Skewness		.291	.687
		Kurtosis		-.078	1.334
	Emax	Mean		.09135000	.004210470
		95% Confidence Interval for Mean	Lower Bound	.08182526	
			Upper Bound	.10087474	

		5% Trimmed Mean		.09133333	
		Median		.09112500	
		Variance		.000	
		Std. Deviation		.013314674	
		Minimum		.072000	
		Maximum		.111000	
		Range		.039000	
		Interquartile Range		.019875	
		Skewness		.125	.687
		Kurtosis		-.671	1.334
	LiSi	Mean		.07785000	.005669142
		95% Confidence Interval for Mean	Lower Bound	.06502551	
			Upper Bound	.09067449	
		5% Trimmed Mean		.07825000	
		Median		.07650000	
		Variance		.000	
		Std. Deviation		.017927400	
		Minimum		.050250	
		Maximum		.098250	
		Range		.048000	
		Interquartile Range		.034125	
		Skewness		-.141	.687
		Kurtosis		-1.709	1.334
Cervical	Cera	Mean		.12712500	.013301538

	95% Confidence Interval for Mean	Lower Bound	.09703483	
		Upper Bound	.15721517	
	5% Trimmed Mean		.12704167	
	Median		.13625000	
	Variance		.002	
	Std. Deviation		.042063155	
	Minimum		.076000	
	Maximum		.179750	
	Range		.103750	
	Interquartile Range		.082313	
	Skewness		-.134	.687
	Kurtosis		-2.002	1.334
Emax	Mean		.09462500	.003681646
	95% Confidence Interval for Mean	Lower Bound	.08629654	
		Upper Bound	.10295346	
	5% Trimmed Mean		.09505556	
	Median		.09537500	
	Variance		.000	
	Std. Deviation		.011642385	
	Minimum		.072250	
	Maximum		.109250	
	Range		.037000	
	Interquartile Range		.019562	

		Skewness		-.593	.687
		Kurtosis		-.151	1.334
	LiSi	Mean		.09245000	.005844133
		95% Confidence Interval for Mean	Lower Bound	.07922965	
			Upper Bound	.10567035	
		5% Trimmed Mean		.09254167	
		Median		.08650000	
		Variance		.000	
		Std. Deviation		.018480771	
		Minimum		.064250	
		Maximum		.119000	
		Range		.054750	
		Interquartile Range		.031000	
		Skewness		.335	.687
		Kurtosis		-.827	1.334
Axial	Cera	Mean		.12485000	.009101602
		95% Confidence Interval for Mean	Lower Bound	.10426074	
			Upper Bound	.14543926	
		5% Trimmed Mean		.12383333	
		Median		.12175000	
		Variance		.001	
		Std. Deviation		.028781794	
		Minimum		.090500	

	Maximum		.177500	
	Range		.087000	
	Interquartile Range		.044750	
	Skewness		.682	.687
	Kurtosis		-.312	1.334
Emax	Mean		.06775000	.007523759
	95% Confidence Interval for Mean	Lower Bound	.05073008	
		Upper Bound	.08476992	
	5% Trimmed Mean		.06561111	
	Median		.06175000	
	Variance		.001	
	Std. Deviation		.023792214	
	Minimum		.045500	
	Maximum		.128500	
	Range		.083000	
	Interquartile Range		.014500	
	Skewness		2.191	.687
	Kurtosis		5.242	1.334
LiSi	Mean		.07755000	.008011953
	95% Confidence Interval for Mean	Lower Bound	.05942570	
		Upper Bound	.09567430	
	5% Trimmed Mean		.07552778	
	Median		.07250000	

		Variance		.001	
		Std. Deviation		.025336020	
		Minimum		.053500	
		Maximum		.138000	
		Range		.084500	
		Interquartile Range		.027375	
		Skewness		1.743	.687
		Kurtosis		3.246	1.334
Pulpal	Cera	Mean		.15732500	.010869941
		95% Confidence Interval for Mean	Lower Bound	.13273548	
			Upper Bound	.18191452	
		5% Trimmed Mean		.15625000	
		Median		.15362500	
		Variance		.001	
		Std. Deviation		.034373773	
		Minimum		.117500	
		Maximum		.216500	
		Range		.099000	
		Interquartile Range		.067000	
		Skewness		.489	.687
		Kurtosis		-1.121	1.334
	Emax	Mean		.11672500	.004802408
		95% Confidence Interval for Mean	Lower Bound	.10586120	

			Upper Bound	.12758880	
		5% Trimmed Mean		.11668056	
		Median		.11375000	
		Variance		.000	
		Std. Deviation		.015186548	
		Minimum		.095750	
		Maximum		.138500	
		Range		.042750	
		Interquartile Range		.025625	
		Skewness		.147	.687
		Kurtosis		-1.360	1.334
	LiSi	Mean		.11175000	.002445233
		95% Confidence Interval for Mean	Lower Bound	.10621850	
			Upper Bound	.11728150	
		5% Trimmed Mean		.11172222	
		Median		.11125000	
		Variance		.000	
		Std. Deviation		.007732507	
		Minimum		.097000	
		Maximum		.127000	
		Range		.030000	
		Interquartile Range		.007438	
		Skewness		.116	.687

		Kurtosis		1.978	1.334
Internal	Cera	Mean		.13875000	.009941398
		95% Confidence Interval for Mean	Lower Bound	.11626100	
			Upper Bound	.16123900	
		5% Trimmed Mean		.13845556	
		Median		.13940000	
		Variance		.001	
		Std. Deviation		.031437460	
		Minimum		.098400	
		Maximum		.184400	
		Range		.086000	
		Interquartile Range		.055900	
		Skewness		.088	.687
		Kurtosis		-1.693	1.334
	Emax	Mean		.09809000	.002598651
		95% Confidence Interval for Mean	Lower Bound	.09221144	
			Upper Bound	.10396856	
		5% Trimmed Mean		.09755000	
		Median		.09595000	
		Variance		.000	
		Std. Deviation		.008217657	
		Minimum		.089600	
		Maximum		.116300	

		Range		.026700	
		Interquartile Range		.011575	
		Skewness		1.234	.687
		Kurtosis		1.516	1.334
	LiSi	Mean		.09719000	.003569110
		95% Confidence Interval for Mean	Lower Bound	.08911611	
			Upper Bound	.10526389	
		5% Trimmed Mean		.09670556	
		Median		.09330000	
		Variance		.000	
		Std. Deviation		.011286516	
		Minimum		.083100	
		Maximum		.120000	
		Range		.036900	
		Interquartile Range		.016450	
		Skewness		1.081	.687
		Kurtosis		.523	1.334
MarginalCem	Cera	Mean		.1054	.01276
		95% Confidence Interval for Mean	Lower Bound	.0765	
			Upper Bound	.1342	
		5% Trimmed Mean		.1032	
		Median		.0980	
		Variance		.002	

		Std. Deviation		.04035	
		Minimum		.06	
		Maximum		.19	
		Range		.14	
		Interquartile Range		.05	
		Skewness		1.055	.687
		Kurtosis		1.625	1.334
	Emax	Mean		.0896	.00520
		95% Confidence Interval for Mean	Lower Bound	.0778	
			Upper Bound	.1013	
		5% Trimmed Mean		.0887	
		Median		.0874	
		Variance		.000	
		Std. Deviation		.01645	
		Minimum		.07	
		Maximum		.13	
		Range		.06	
		Interquartile Range		.02	
		Skewness		1.154	.687
		Kurtosis		1.559	1.334
	LiSi	Mean		.0691	.00345
		95% Confidence Interval for Mean	Lower Bound	.0613	
			Upper Bound	.0769	

		5% Trimmed Mean		.0695	
		Median		.0710	
		Variance		.000	
		Std. Deviation		.01090	
		Minimum		.05	
		Maximum		.08	
		Range		.04	
		Interquartile Range		.01	
		Skewness		-1.099	.687
		Kurtosis		1.370	1.334
CervicalCem	Cera	Mean		.1441	.00706
		95% Confidence Interval for Mean	Lower Bound	.1281	
			Upper Bound	.1600	
		5% Trimmed Mean		.1444	
		Median		.1420	
		Variance		.000	
		Std. Deviation		.02232	
		Minimum		.10	
		Maximum		.18	
		Range		.08	
		Interquartile Range		.03	
		Skewness		-.279	.687
		Kurtosis		.952	1.334
	Emax	Mean		.1037	.00696

		95% Confidence Interval for Mean	Lower Bound	.0880	
			Upper Bound	.1195	
		5% Trimmed Mean		.1029	
		Median		.1054	
		Variance		.000	
		Std. Deviation		.02202	
		Minimum		.08	
		Maximum		.15	
		Range		.07	
		Interquartile Range		.03	
		Skewness		.489	.687
		Kurtosis		-.444	1.334
	LiSi	Mean		.0925	.00674
		95% Confidence Interval for Mean	Lower Bound	.0772	
			Upper Bound	.1077	
		5% Trimmed Mean		.0918	
		Median		.0955	
		Variance		.000	
		Std. Deviation		.02131	
		Minimum		.07	
		Maximum		.13	
		Range		.06	
		Interquartile Range		.04	

		Skewness		.390	.687
		Kurtosis		-.812	1.334
AxialCem	Cera	Mean		.1273	.01185
		95% Confidence Interval for Mean	Lower Bound	.1005	
			Upper Bound	.1541	
		5% Trimmed Mean		.1258	
		Median		.1170	
		Variance		.001	
		Std. Deviation		.03746	
		Minimum		.08	
		Maximum		.20	
		Range		.12	
		Interquartile Range		.06	
		Skewness		.898	.687
		Kurtosis		.409	1.334
	Emax	Mean		.0758	.00457
		95% Confidence Interval for Mean	Lower Bound	.0654	
			Upper Bound	.0861	
		5% Trimmed Mean		.0750	
		Median		.0720	
		Variance		.000	
		Std. Deviation		.01444	
		Minimum		.06	

		Maximum		.11	
		Range		.05	
		Interquartile Range		.02	
		Skewness		.981	.687
		Kurtosis		.310	1.334
	LiSi	Mean		.0899	.01308
		95% Confidence Interval for Mean	Lower Bound	.0603	
			Upper Bound	.1194	
		5% Trimmed Mean		.0886	
		Median		.0793	
		Variance		.002	
		Std. Deviation		.04137	
		Minimum		.04	
		Maximum		.16	
		Range		.12	
		Interquartile Range		.08	
		Skewness		.528	.687
		Kurtosis		-1.124	1.334
PulpalCem	Cera	Mean		.1669	.00725
		95% Confidence Interval for Mean	Lower Bound	.1505	
			Upper Bound	.1833	
		5% Trimmed Mean		.1673	
		Median		.1626	

	Variance		.001	
	Std. Deviation		.02293	
	Minimum		.13	
	Maximum		.20	
	Range		.08	
	Interquartile Range		.04	
	Skewness		.085	.687
	Kurtosis		-.064	1.334
Emax	Mean		.1306	.00840
	95% Confidence Interval for Mean	Lower Bound	.1116	
		Upper Bound	.1496	
	5% Trimmed Mean		.1306	
	Median		.1324	
	Variance		.001	
	Std. Deviation		.02657	
	Minimum		.09	
	Maximum		.17	
	Range		.08	
	Interquartile Range		.05	
	Skewness		.006	.687
	Kurtosis		-1.464	1.334
LiSi	Mean		.1264	.00743
	95% Confidence Interval for Mean	Lower Bound	.1096	

			Upper Bound	.1432	
		5% Trimmed Mean		.1262	
		Median		.1219	
		Variance		.001	
		Std. Deviation		.02348	
		Minimum		.09	
		Maximum		.17	
		Range		.08	
		Interquartile Range		.04	
		Skewness		.212	.687
		Kurtosis		-.825	1.334
InternalCem	Cera	Mean		.1498	.00425
		95% Confidence Interval for Mean	Lower Bound	.1402	
			Upper Bound	.1595	
		5% Trimmed Mean		.1496	
		Median		.1504	
		Variance		.000	
		Std. Deviation		.01344	
		Minimum		.13	
		Maximum		.17	
		Range		.04	
		Interquartile Range		.02	
		Skewness		.085	.687

	Kurtosis		.111	1.334
Emax	Mean		.1089	.00659
	95% Confidence Interval for Mean	Lower Bound	.0940	
		Upper Bound	.1238	
	5% Trimmed Mean		.1083	
	Median		.1079	
	Variance		.000	
	Std. Deviation		.02083	
	Minimum		.08	
	Maximum		.14	
	Range		.06	
	Interquartile Range		.04	
	Skewness		.310	.687
	Kurtosis		-.964	1.334
LiSi	Mean		.1055	.00565
	95% Confidence Interval for Mean	Lower Bound	.0927	
		Upper Bound	.1183	
	5% Trimmed Mean		.1048	
	Median		.1014	
	Variance		.000	
	Std. Deviation		.01787	
	Minimum		.08	

	Maximum	.14	
	Range	.06	
	Interquartile Range	.02	
	Skewness	.768	.687
	Kurtosis	.757	1.334

Kruskal-Wallis Test

Comparing the different 2D measuring points between the three tested material (pre-bonding)

Test Statistics[a,b]

	Absolute marginal discrepancy	Marginal discrepancy	Cervical seat	Cervico-axial angle	Axial wall	Pulpal angle	Pulpal floor
Chi-Square	2.453	3.441	5.722	3.727	14.641	11.871	8.083
df	2	2	2	2	2	2	2
Asymp. Sig.	.293	.179	.057	.155	.001	.003	.018

a. Kruskal Wallis Test

b. Grouping Variable: V1

Kruskal-Wallis Test

Comparing the 2D ROI’s measurements between the three tested materials (pre-bonding)

Test Statistics[a,b]

	Marginal	Cervical	Axial	Pulpal	Internal
Chi-Square	3.021	2.941	14.641	13.567	13.368
df	2	2	2	2	2
Asymp. Sig.	.221	.230	.001	.001	.001

a. Kruskal Wallis Test

b. Grouping Variable: V1

Kruskal-Wallis Test

Comparing the 2D ROI's measurements between the three tested materials (post-bonding)

Test Statistics[a,b]

	MarginalCem	CervicalCem	AxialCem	PulpalCem	InternalCem
Chi-Square	10.333	14.965	9.970	10.954	16.849
df	2	2	2	2	2
Asymp. Sig.	.006	.001	.007	.004	.000

a. Kruskal Wallis Test

b. Grouping Variable: V1

Mann-Whitney Test

Comparing the different 2D measuring points between Cerasmart and Emax

Test Statistics[a]

	Cervical seat	Cervico-axial angle	Axial wall	Pulpal angle	Pulpal floor
Mann-Whitney U	32.000	27.500	7.000	14.000	17.500
Wilcoxon W	87.000	82.500	62.000	69.000	72.500
Z	-1.362	-1.702	-3.250	-2.722	-2.458
Asymp. Sig. (2-tailed)	.173	.089	.001	.006	.014
Exact Sig. [2*(1-tailed Sig.)]	.190[b]	.089[b]	.000[b]	.005[b]	.011[b]

a. Grouping Variable: V1

b. Not corrected for ties.

Mann-Whitney Test

Comparing the different 2D measuring points between Cerasmart and Emax blocks

Test Statistics[a]

	Cervical seat	Cervico-axial angle	Axial wall	Pulpal angle	Pulpal floor	Absolute marginal discrepancy	Marginal discrepancy
Mann-Whitney U	32.000	27.500	7.000	14.000	17.500	48.500	46.500
Wilcoxon W	87.000	82.500	62.000	69.000	72.500	103.500	101.500
Z	-1.362	-1.702	-3.250	-2.722	-2.458	-.113	-.265
Asymp. Sig. (2-tailed)	.173	.089	.001	.006	.014	.910	.791

Exact Sig. [2*(1-tailed Sig.)]	.190[b]	.089[b]	.000[b]	.005[b]	.011[b]	.912[b]	.796[b]

a. Grouping Variable: V1

b. Not corrected for ties.

Mann-Whitney Test

Comparing the different 2D measuring points between Cerasmart and LiSi blocks

Test Statistics[a]

	Cervical seat	Cervico-axial angle	Axial wall	Pulpal angle	Pulpal floor	Absolute marginal discrepancy	Marginal discrepancy
Mann-Whitney U	22.500	38.500	9.000	11.000	18.000	33.000	28.500
Wilcoxon W	77.500	93.500	64.000	66.000	73.000	88.000	83.500
Z	-2.080	-.870	-3.099	-2.948	-2.420	-1.285	-1.627
Asymp. Sig. (2-tailed)	.037	.384	.002	.003	.016	.199	.104

Exact Sig. [2*(1-tailed Sig.)]	.035[b]	.393[b]	.001[b]	.002[b]	.015[b]	.218[b]	.105[b]

a. Grouping Variable: V1

b. Not corrected for ties.

Mann-Whitney Test

Comparing the different 2D measuring points between Emax and LiSi blocks

Test Statistics[a]

	Cervical seat	Cervico-axial angle	Axial wall	Pulpal angle	Pulpal floor	Absolute marginal discrepancy	Marginal discrepancy
Mann-Whitney U	29.000	31.500	31.500	32.000	47.000	31.500	29.500
Wilcoxon W	84.000	86.500	86.500	87.000	102.000	86.500	84.500
Z	-1.588	-1.400	-1.399	-1.361	-.227	-1.399	-1.550
Asymp. Sig. (2-tailed)	.112	.162	.162	.173	.821	.162	.121
Exact Sig. [2*(1-tailed Sig.)]	.123[b]	.165[b]	.165[b]	.190[b]	.853[b]	.165[b]	.123[b]

a. Grouping Variable: V1

b. Not corrected for ties.

Mann-Whitney Test

Comparing the different ROI's measuring points between Cerasmart and Emax blocks

Test Statistics[a]

	Marginal	Cervical	Axial	Pulpal	Internal
Mann-Whitney U	49.000	34.000	7.000	14.000	8.000
Wilcoxon W	104.000	89.000	62.000	69.000	63.000
Z	-.076	-1.209	-3.250	-2.722	-3.175
Asymp. Sig. (2-tailed)	.940	.226	.001	.006	.001
Exact Sig. [2*(1-tailed Sig.)]	.971[b]	.247[b]	.000[b]	.005[b]	.001[b]

a. Grouping Variable: V1

b. Not corrected for ties.

Mann-Whitney Test

Comparing the different ROI's measuring points between Cerasmart and LiSi blocks

Test Statistics[a]

	Marginal	Cervical	Axial	Pulpal	Internal
Mann-Whitney U	31.000	28.000	9.000	3.500	9.000
Wilcoxon W	86.000	83.000	64.000	58.500	64.000
Z	-1.436	-1.664	-3.099	-3.518	-3.100
Asymp. Sig. (2-tailed)	.151	.096	.002	.000	.002
Exact Sig. [2*(1-tailed Sig.)]	.165[b]	.105[b]	.001[b]	.000[b]	.001[b]

a. Grouping Variable: V1

b. Not corrected for ties.

Mann-Whitney Test

Comparing the different ROI's measuring points between Emax and LiSi blocks

Test Statistics[a]

	Marginal	Cervical	Axial	Pulpal	Internal
Mann-Whitney U	29.500	45.500	31.500	43.000	46.000
Wilcoxon W	84.500	100.500	86.500	98.000	101.000
Z	-1.550	-.340	-1.399	-.529	-.302
Asymp. Sig. (2-tailed)	.121	.734	.162	.597	.762
Exact Sig. [2*(1-tailed Sig.)]	.123[b]	.739[b]	.165[b]	.631[b]	.796[b]

a. Grouping Variable: V1

b. Not corrected for ties.

Wilcoxon Signed Ranks Test

Comparing the different ROI's measuring points before and after cementation between Cerasmart and Emax

Test Statistics[a]

	MarginalCem - Marginal	CervicalCem - Cervical	AxialCem - Axial	PulpalCem - Pulpal	InternalCem - Internal
Z	-.969[b]	-.663[b]	-.357[c]	-1.172[b]	-.663[b]

Asymp. Sig. (2-tailed)	.333	.507	.721	.241	.508

a. Wilcoxon Signed Ranks Test

b. Based on negative ranks.

c. Based on positive ranks.

Wilcoxon Signed Ranks Test

Comparing the different ROI's measuring points before and after cementation between Cerasmart and LiSi blocks

Test Statistics[a]

	MarginalCem - Marginal	CervicalCem - Cervical	AxialCem - Axial	PulpalCem - Pulpal	InternalCem - Internal
Z	-.561[b]	-.714[c]	-1.172[c]	-1.580[c]	-1.478[c]
Asymp. Sig. (2-tailed)	.575	.475	.241	.114	.139

a. Wilcoxon Signed Ranks Test

b. Based on positive ranks.

c. Based on negative ranks.

Wilcoxon Signed Ranks Test

Comparing the different ROI's measuring points before and after cementation between Emax and LiSi blocks

Test Statistics[a]

	MarginalCem - Marginal	CervicalCem - Cervical	AxialCem - Axial	PulpalCem - Pulpal	InternalCem - Internal
Z	-1.327[b]	-.764[c]	-1.070[c]	-1.682[c]	-1.886[c]
Asymp. Sig. (2-tailed)	.185	.445	.285	.093	.059

a. Wilcoxon Signed Ranks Test

b. Based on positive ranks.

c. Based on negative ranks.

Nonparametric Tests

Compare between different ROI'S within each material

FRIEDMAN Test (COM PARE=PAIRWISE)

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of Absolute marginal discrepancy is the same across categories of V1.	Independent-Samples Kruskal-Wallis Test	.293	Retain the null hypothesis.
2	The distribution of Marginal discrepancy is the same across categories of V1.	Independent-Samples Kruskal-Wallis Test	.179	Retain the null hypothesis.
3	The distribution of Cervical seat is the same across categories of V1.	Independent-Samples Kruskal-Wallis Test	.057	Retain the null hypothesis.
4	The distribution of Cervico-axial angle is the same across categories of V1.	Independent-Samples Kruskal-Wallis Test	.155	Retain the null hypothesis.
5	The distribution of Axial wall is the same across categories of V1.	Independent-Samples Kruskal-Wallis Test	.001	Reject the null hypothesis.
6	The distribution of Pulpal angle is the same across categories of V1.	Independent-Samples Kruskal-Wallis Test	.003	Reject the null hypothesis.
7	The distribution of Pulpal floor is the same across categories of V1.	Independent-Samples Kruskal-Wallis Test	.018	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distributions of Marginal, Cervical, Axial and Pulpal are the same.	Related-Samples Friedman's Two-Way Analysis of Variance by Ranks	.003	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

Wilcoxon Signed Ranks Test

Compare between marginal and internal misfits for Cerasmart group

Ranks

		N	Mean Rank	Sum of Ranks
Internal - Marginal	Negative Ranks	0[a]	.00	.00
	Positive Ranks	10[b]	5.50	55.00
	Ties	0[c]		
	Total	10		

a. Internal < Marginal

b. Internal > Marginal

c. Internal = Marginal

Test Statistics[a]

	Internal - Marginal

Z	-2.803[b]
Asymp. Sig. (2-tailed)	.005

a. Wilcoxon Signed Ranks Test

b. Based on negative ranks.

*Nonparametric Tests: Related Samples.

```
NPTESTS
  /RELATED TEST(Marginal Cervical Axial Pulpal)
FRIEDMAN(COMPARE=PAIRWISE)
  /MISSING SCOPE=ANALYSIS USERMISSING=EXCLUDE
  /CRITERIA ALPHA=0.05  CILEVEL=95.
```

Nonparametric Tests

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distributions of Marginal, Cervical, Axial and Pulpal are the same.	Related-Samples Friedman's Two-Way Analysis of Variance by Ranks	.001	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

Wilcoxon Signed Ranks Test

Compare between marginal and internal misfits for Emax group

Ranks

		N	Mean Rank	Sum of Ranks
Internal - Marginal	Negative Ranks	3[a]	4.67	14.00
	Positive Ranks	7[b]	5.86	41.00
	Ties	0[c]		
	Total	10		

a. Internal < Marginal

b. Internal > Marginal

c. Internal = Marginal

Test Statistics[a]

	Internal - Marginal
Z	-1.376[b]
Asymp. Sig. (2-tailed)	.169

a. Wilcoxon Signed Ranks Test

b. Based on negative ranks.

Nonparametric Tests

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distributions of Marginal, Cervical, Axial and Pulpal are the same.	Related-Samples Friedman's Two-Way Analysis of Variance by Ranks	.004	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

Wilcoxon Signed Ranks Test

Compare between marginal and internal misfits for LiSi group

Ranks

		N	Mean Rank	Sum of Ranks
Internal - Marginal	Negative Ranks	2[a]	2.00	4.00
	Positive Ranks	8[b]	6.38	51.00
	Ties	0[c]		
	Total	10		

a. Internal < Marginal

b. Internal > Marginal

c. Internal = Marginal

Test Statistics[a]

	Internal - Marginal
Z	-2.395[b]
Asymp. Sig. (2-tailed)	.017

a. Wilcoxon Signed Ranks Test

b. Based on negative ranks.

DATASET ACTIVATE DataSet1.

Appendix C

Fitting surface roughness data analysis

Kruskal-Wallis Test

Compare the different roughness measurement (Ra, Rq, Rp, Rv) values of internal fitting surfaces between the three tested materials

Ranks

	Groups	N	Mean Rank
Ra	cera	20	41.33
	emax	20	36.48
	lisi	20	13.70
	Total	60	
Rq	cera	20	43.90
	emax	20	33.80
	lisi	20	13.80
	Total	60	
Rp	cera	20	37.15
	emax	20	43.50
	lisi	20	10.85
	Total	60	
Rv	cera	20	43.05
	emax	20	36.05
	lisi	20	12.40
	Total	60	

Test Statistics[a,b]

	Ra	Rq	Rp	Rv
Chi-Square	28.536	30.783	39.302	33.831
df	2	2	2	2
Asymp. Sig.	.000	.000	.000	.000

a. Kruskal Wallis Test

b. Grouping Variable: Groups

Mann-Whitney Test

Multiple comparison for the different roughness measurement (Ra, Rq, Rp, Rv) values of internal fitting surfaces between Cerasmart and Emax groups.

Ranks

	Groups	N	Mean Rank	Sum of Ranks
Ra	cera	20	22.63	452.50
	emax	20	18.38	367.50
	Total	40		
Rq	cera	20	25.00	500.00
	emax	20	16.00	320.00
	Total	40		
Rp	cera	20	17.40	348.00
	emax	20	23.60	472.00

	Total	40		
Rv	cera	20	23.55	471.00
	emax	20	17.45	349.00
	Total	40		

Test Statistics[a]

	Ra	Rq	Rp	Rv
Mann-Whitney U	157.500	110.000	138.000	139.000
Wilcoxon W	367.500	320.000	348.000	349.000
Z	-1.150	-2.435	-1.677	-1.650
Asymp. Sig. (2-tailed)	.250	.015	.094	.099
Exact Sig. [2*(1-tailed Sig.)]	.253[b]	.014[b]	.096[b]	.102[b]

a. Grouping Variable: Groups

b. Not corrected for ties.

Mann-Whitney Test

Multiple comparison for the different roughness measurement (Ra, Rq, Rp, Rv) values of internal fitting surfaces between Cerasmart and LiSi groups.

Ranks

	Groups	N	Mean Rank	Sum of Ranks
Ra	cera	20	29.20	584.00
	lisi	20	11.80	236.00

	Total	40		
Rq	cera	20	29.40	588.00
	lisi	20	11.60	232.00
	Total	40		
Rp	cera	20	30.25	605.00
	lisi	20	10.75	215.00
	Total	40		
Rv	cera	20	30.00	600.00
	lisi	20	11.00	220.00
	Total	40		

Test Statistics[a]

	Ra	Rq	Rp	Rv
Mann-Whitney U	26.000	22.000	5.000	10.000
Wilcoxon W	236.000	232.000	215.000	220.000
Z	-4.707	-4.816	-5.275	-5.140
Asymp. Sig. (2-tailed)	.000	.000	.000	.000
Exact Sig. [2*(1-tailed Sig.)]	.000[b]	.000[b]	.000[b]	.000[b]

a. Grouping Variable: Groups

b. Not corrected for ties.

Mann-Whitney Test

Multiple comparison for the different roughness measurement (Ra, Rq, Rp, Rv) values of internal fitting surfaces between Emax and LiSi groups.

Ranks

	Groups	N	Mean Rank	Sum of Ranks
Ra	emax	20	28.60	572.00
	lisi	20	12.40	248.00
	Total	40		
Rq	emax	20	28.30	566.00
	lisi	20	12.70	254.00
	Total	40		
Rp	emax	20	30.40	608.00
	lisi	20	10.60	212.00
	Total	40		
Rv	emax	20	29.10	582.00
	lisi	20	11.90	238.00
	Total	40		

Test Statistics[a]

	Ra	Rq	Rp	Rv
Mann-Whitney U	38.000	44.000	2.000	28.000
Wilcoxon W	248.000	254.000	212.000	238.000
Z	-4.383	-4.221	-5.356	-4.653
Asymp. Sig. (2-tailed)	.000	.000	.000	.000
Exact Sig. [2*(1-tailed Sig.)]	.000[b]	.000[b]	.000[b]	.000[b]

a. Grouping Variable: Groups

b. Not corrected for ties.