INFLUENCE OF VARIATIONS IN CERAMIC THICKNESS AND BONDING SUBSTRATE ON THE FRACTURE RESISTANCE OF LITHIUM DISILICATE RESTORATIONS

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DECLARATION

I declare that *INFLUENCE OF VARIATIONS IN CERAMIC THICKNESS AND BONDING SUBSTRATE ON THE FRACTURE RESISTANCE OF LITHIUM DISILICATE RESTORATIONS* is my own work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

Full name.........Jean Alexander van LIerop Date.........31 May 2018........................

Signed.......................................

ABSTRACT

INFLUENCE OF VARIATIONS IN CERAMIC THICKNESS AND BONDING SUBSTRATE ON THE FRACTURE RESISTANCE OF LITHIUM DISILICATE RESTORATIONS

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Introduction: Restorative dentistry aims to replace lost or damaged tooth structure with durable and life-like alternatives. To accommodate the inherent limitations and weakness of the restorative materials, preparation techniques often require the sacrifice of healthy tooth structure to create enough restorative space. This can lead to weakening of the remaining tooth structure, with subsequent damage or catastrophic failure. When using indirect restoratives, the development of adhesive luting agents (adhesive cements) and stronger all-porcelain restorations (lithium disilicate) has contributed to the development of “minimally invasive” preparation techniques and concepts such as cavity design optimization (CDO) and bio-substitution. With these techniques, resin materials are combined with ceramic restoratives in an attempt to not only produce strong restorations, but also increase the longevity of the remaining tooth. The clinician needs to therefore find the ideal preparation design that combine such materials to produces a clinically performing restoration while increasing the strength and longevity of the underlying tooth.

Aim of study: The aim of this in vitro study was to evaluate the influence of ceramic thickness and variations in cavity design on the fracture resistance and mode of fracture of lithium disilicate ceramic restorations.

Materials and methods: Forty human molar teeth were prepared for an occlusal veneer restoration with an additional occlusal (class 1) defect. These were divided randomly into two groups ($n = 20$). In Group A, a bonded resin restoration was used to fill the class 1 defect and in Group B, the defect was left unfilled. For both groups, CAD/CAM monolithic lithium disilicate restorations were designed and manufactured to create ceramic restoration with thickness of 1mm (subgroup 1, n - 10) and 0.8mm (subgroup 2, n - 10) over the cusp. Ceramic restorations were adhesively bonded to the tooth and then thermo-cycled. All specimens were incrementally loaded and evaluated for initial crack formation after which they were statically loaded to failure.

Data Analysis: A Kruskal-Wallis analyses with group and thickness as independent variables was evaluated. The mean fracture values expressed in Newtons (N) were compared for statistical differences and a p value < 0.05 was considered as significant. In addition, the mode of fracture was evaluated and categorised according to restorability.

Results: In Group A, the maximum fracture strength of the ceramic with thickness 1mm over the cusp (A1) was significantly higher than that of 0.8mm (A2). For Group B, this change was not significant. At 1mm thickness over the cusp, Groups A and B showed no statistically significant difference in the maximum fracture resistance, whereas at 0,8mm, a significant difference was noted. When evaluating the mode of fracture, the porcelain thickness of 1mm in Group A showed 30% un-restorable fractures, which increased to 70% in Group B.

Conclusion: When using ceramic to restore defects where large volumes of dentine has been lost, a lithium disilicate restoration with thickness of 1.0 mm over the cusp, in combination with direct restoratives using cavity design optimization (CDO), can be recommended to achieve functionaly stable restorations that contribute to the longevity of the remaing tooth.

KEYWORDS

- Adhesives
- Lithium-disilicate
- Minimally invasive dentistry
- Cavity design optimisation
- Resin
- Occlusal veneer
- Thickness
- Fracture strength
- Longevity
- Repairability

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Introduction

One of the primary goals of restorative dentistry is to replace lost or damaged tooth structure with durable and aesthetic alternatives that can create life-like function and appearance. In some clinical situations, the amount of tooth structure that has been lost forces the clinician to opt for the use of indirect restorative techniques that will create the functional and durable restorations that are needed (Smithson *et al.*, 2011). Traditionally, this has been achieved through the use of laboratory manufactured all-metal or metal-ceramic restorations that were cemented to a previously shaped tooth (Seymour, Samarawickrama and Lynch, 1999). To facilitate the durable retention of such restorations, physically retentive preparation designs were needed. These preparation designs often led to the sacrifice of healthy tooth structure, in order to allow for the creation of adequate long-term retention (Edelhoff, 2002).

The advancements in dental adhesives, together with the subsequent increase in the strength of the resin to tooth bond, have led to the development of adhesive luting agents that reduce the need for mechanical retention of restorations (Blatz and Sadan, 2003). These developments have coincided with the development of stronger all-porcelain restorations, most notably that of lithium disilicate (Politano *et al.*, 2016). By adhesively luting these strong porcelain restorations to the tooth structure, a synergy is created and the restoration and the tooth become mutually supportive, thereby reducing the need for overly aggressive preparation designs (Dietschi and Spreafico, 2015).

The introduction of predictable adhesive technologies has led to a giant leap in interest in minimally invasive dentistry (Ericson, 2004). This concept is aimed at reducing the amount of tooth structure sacrificed in order to produce long lasting restorations. These developments have caused a shift in clinical dentistry to that of a more conservative treatment approach. One that is based on the use of adhesive techniques and conservative restorations that require the minimal sacrifice of healthy tooth structure (Dietschi and Spreafico, 2015).

The concept of "Biomimetic" dentistry further develops the minimally invasive approach (Magne and Douglas, 1999). In the biomimetic approach, the ideal restoration aims to duplicate nature. Tooth structure is replaced with materials that show tooth-like properties. Therefore, dentine is replaced with a dentine-like material (currently resin composite) and enamel with an enamel-like material (currently porcelain) (Tirlet *et al.*, 2014). The development of these techniques has seen the combination of restorative materials in an attempt to produce clinically strong restorations while also increasing the longevity of the underlying tooth (Veneziani, 2017).

Using these modern concepts and materials, clinicians have pushed the boundaries in clinical practice, achieving remarkably long-lasting results. This has given rise to a number of questions:

- What is the ideal preparation design, and how predictable are these ultra-thin, conservative porcelain?
- Does the use of composite as dentine replacement increase the fracture resistance of the ultra-thin ceramics?
- What is the ideal thickness of such thin porcelain restorations?
- What is the impact of such techniques on the longevity of the underlying tooth?

Therefore, the aim of this *in-vitro* study is to evaluate the influence of variations in ceramic thickness and cavity design on the fracture resistance of the lithium disilicate ceramic restorations.

CHAPTER 1

Literature review

In many circumstances, the amount of tooth structure that had been lost due to carious destruction or fracture forces the clinician to use indirect restorative techniques, such as full coverage crowns and porcelain overlays or inlays, in order to create functional and durable restorations (Smithson *et al.*, 2011). Traditionally, these indirect restorative materials required a physically retentive preparation design to help achieve better retention (Seymour, Samarawickrama and Lynch, 1999). Some materials were inherently weak and needed additional thickness to create clinically durable restorations (Federlin *et al.*, 2007). These limitations meant that additional restorative space needed to be created, leading to aggressive preparation designs and the sacrifice of healthy tooth structure to achieve restorations that are clinically acceptable.

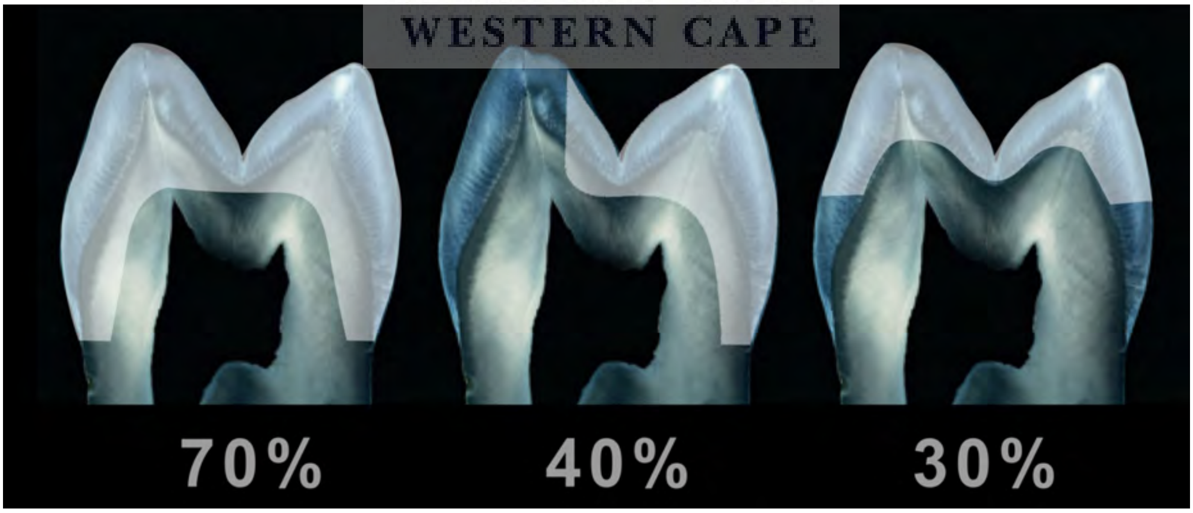


Figure 1: Percentage of tooth structure removal associated with various preparation designs in posterior teeth (adapted from Edelhoff *et al.*, 2002)

The first graphic shows the design of a full coverage crown. The second, a partial crown and the last that of a conservative onlay.

Analyses of various preparation designs in posterior teeth have shown that the amount of tooth structure removed during traditional complete coverage crown preparation can be as much as 40% greater than that of more conservative onlay and partial crown preparation designs (Figure 1) (Edelhoff, 2002). This increased removal of tooth structure leads to significant reductions in both cusp stiffness (Magne & Belser, 2003) and tooth strength (St-Georges et al., 2003).

The combination of excessive cavity preparation with lateral masticatory forces, create shearing and tensile stresses within the tooth, which can lead to complete, or incomplete vertical root fractures (Dejak and Młotkowski, 2015). This increased vulnerability causes fracture failures that typically involve the restoration and the underlying tooth structure and is most commonly seen as catastrophic (Beier *et al.*, 2012).

These preparation designs can also have an adverse effect on pulpal health. Studies have shown the development of pulpal necrosis after construction of fixed prostheses Cheung *et al.* (2005) showed that three of 73 previously vital teeth restored with single crowns were deemed to have failed because they became peri-apically involved or had been root canal treated after a mean observation period of 34 months. This equates to 4% of vital teeth developing pulpal necrosis after placement of single crowns. Saunders & Saunders (1998) conducted a cross-sectional, radiographic survey on patients for whom sets of full-mouth periapical radiographs were available. They reported that 19% of initially vital teeth developed periradicular radiolucency after crown placement (Saunders & Saunders, 1998).

With the advent of adhesive bonding and strong all-porcelain restorations, the goal of minimising the volume of tooth structure loss due to preparation design has been realised. This is possible through the use of adhesive luting agents that bond the restoration and underlying tooth structure together, reducing the need for the mechanical retention of restorative materials (Blatz and Sadan, 2003). The success of such conservative bonded porcelain restorations is supported by a study conducted by Cheung (1991), which showed that the failure rates of single tooth restorations ranged from 2.4 per cent to 7.8 per cent for different crowns in the following order: partial veneer less than full veneer less than metal ceramic less than porcelain jacket crowns (Cheung, 1991).

The adhesive bonding of restorations has seen the rise to the "conservative" or "minimally invasive" dentistry concept (Ericson, 2004). This concept is aimed at reducing the amount of healthy tooth structure sacrificed in order to produce long-lasting restorations. These developments caused a shift in clinical dentistry to that of a more conservative treatment approach. Based on the use of adhesive techniques and conservative restorations requiring minimal sacrifice of healthy tooth structure (Dietschi & Spreafico, 2015). Such conservative preparations increase the longevity of the tooth and restoration (Veneziani, 2017).

1.1 The choice of restorative ceramic

The first fundamental decision a clinician needs to make when restoring an extensively damaged tooth using modern, minimally invasive protocol is the choice of the restorative material. There are a large number of restoratives currently available on the market. These materials vary in their physical properties and uses. The final choice of the restorative material and its inherent physical properties has a direct influence on the other critical components, that of: preparation design, method of processing and the adhesive protocol used (Rocca *et al.*, 2015). Figure 2 indicates the current consensus for the minimum material thickness that is required for some popular materials on the market today (Rocca *et al.*, 2015; Veneziani, 2017).

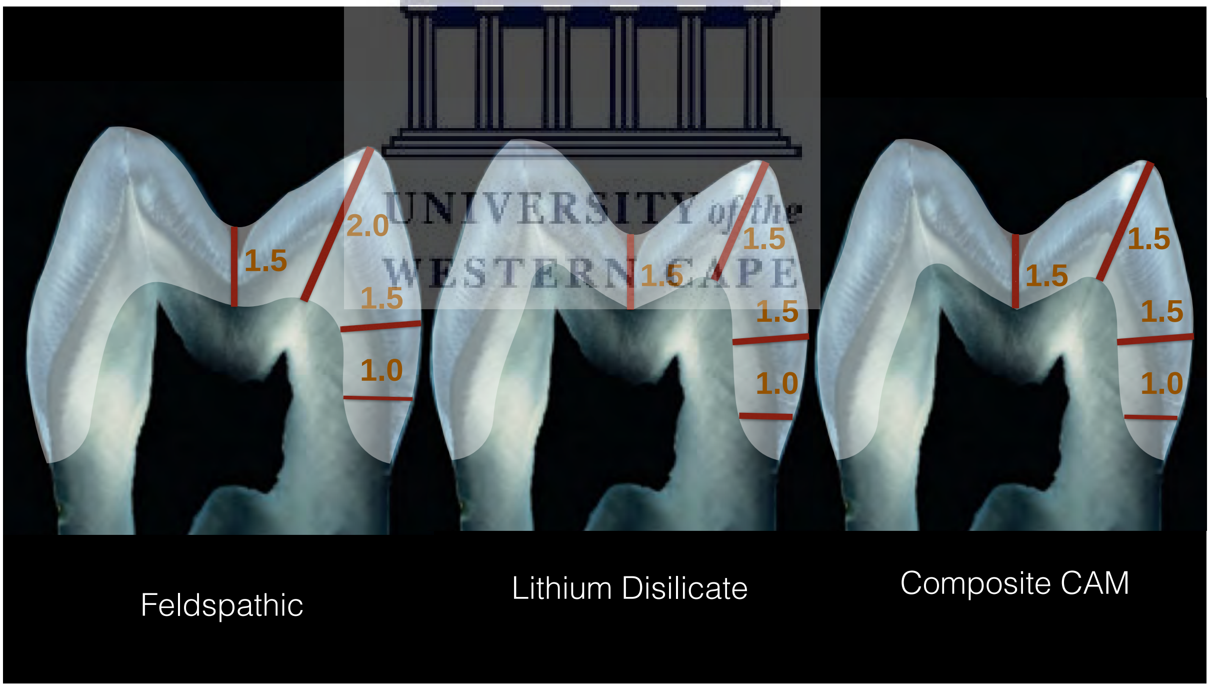


Figure 2: Summary of current preparation guidelines for popular indirect restorative material as indicated by the manufacturers (Rocca *et al.*, 2015)**. These guidelines give an indication of the minimum thickness of restorative material (indicated in mm) for each area of the tooth**

Dental ceramics, with their pleasing aesthetics and ability to be bonded, have historically been the material of choice for indirect restorative treatment. Through the use of coupling agents and adhesive cements, dental ceramics can be adhesively luted to the tooth structure, creating a synergy between the tooth and the restoration.

When exploring the ideal preparation design and restorative thickness, it is important to understand the material that is being used and how this impacts on the restorative process. The literature has identified three main categories of silica-based dental ceramics (Blatz and Sadan, 2003). These categories are as follows:

- predominantly glass ceramics
- polycrystalline (non-glass) ceramics
- particle-filled glass ceramics

1.1.1 Predominantly glass ceramics

This type of ceramic is derived from feldspar minerals, silicone and aluminium oxides. It is used as a veneering material over metal or ceramic copings and frameworks (IPS e.max Ceram Ivoclar Vivadent, N.Y.). Additionally, it is used to fabricate jacket crowns, inlays, onlays and porcelain veneers in high aesthetic-demand cases. This ceramic has low mechanical strength in comparison with other ceramic types and must be adhesively cemented (Vargas *et al*., 2011).

Preparation designs need to take into consideration the inherent weakness of this ceramic and the need for more restorative space. Subsequently, these preparations designs are generally more aggressive. There appears to be a reasonable consensus that the minimum required dimensions for all ceramic posterior inlay and onlay and full crown preparations (see Figure

2) using glass ceramics is 1.5–2 mm of cuspal reduction, 1–1.5 mm of axial reduction, and 2 mm of isthmus width when used as inlay material (Hopp & Land, 2013).

1.1.2 Polycrystalline (non-glass) ceramics

Polycrystalline ceramics are densely sintered aluminium oxide or zirconia materials and are characterised by the absence of glass in their composition (Procera Alumina, Nobel Biocare, Zurich; Lava Zirconia, 3M ESPE; IPS e.max ZirCAD, Ivoclar Vivadent). These ceramics possess high toughness and strength and can be used for copings and framework and monolithic crowns (Vargas *et al*., 2011). However, it is difficult to achieve durable adhesive bonding to its surface due to the material's inert nature and resistance to acid etching or silanisation (Cheung, Botelho and Matinlinna, 2014). It is the author's opinion that this lack of adhesive cementation prevents polycrystalline ceramics from being the material of choice when working in a minimally invasive environment. This is due to the need for more aggressive preparation designs to help create a more physically retentive preparation.

1.1.3 Particle-filled glass ceramics

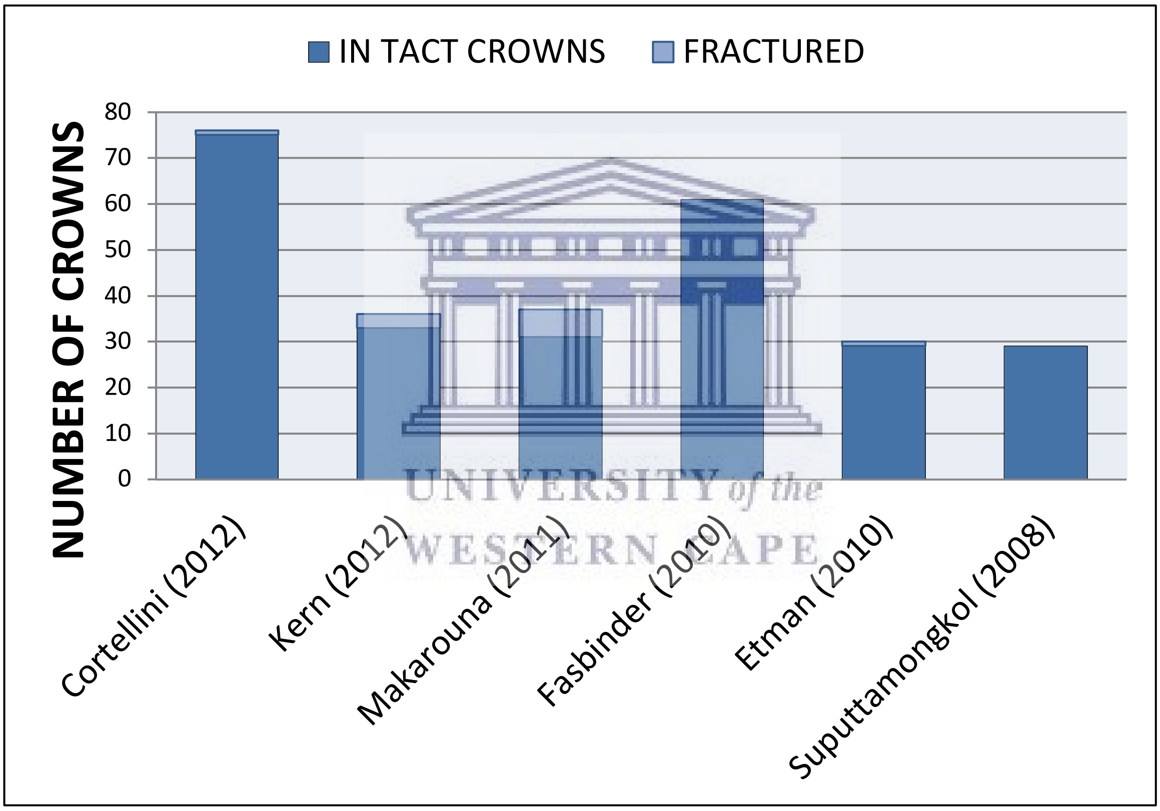
These ceramics consist of various amounts and types of particles in a glassy matrix. Intermediate-filled material, such as IPS e.max Press / IPS e.max CAD (Ivoclar Vivadent) is reinforced with lithium disilicate and its strength and pleasing aesthetic properties are sufficient to allow for its use in veneers, single crowns and copings (Ivoclar-Vivadent-AG, 2013). This material can be cemented either adhesively or non-adhesively when it is used with full-coverage restorations. These properties have made particle-filled ceramics a popular restorative material in a minimally invasive protocol (Christensen, 2011).

The evolution of the particle-filled glass ceramic, lithium disilicate, as a restorative material dates back to 1998, when it was introduced to dentistry as IPS Empress 2 (Ivoclar Vivadent). It was the second generation of heat-pressed ceramic and contained lithium disilicate material as the main crystalline phase. The manufacturer's indications for this material ranged from veneers, inlays, onlays and crowns, to 3-unit fixed dental prostheses (FDP's) in the anterior region (Pieger *et al*., 2014). The manufacturer eventually discontinued this material, and a reformulated and optimised composition of lithium disilicate ceramic was introduced under the trade name IPS e.max (Ivoclar Vivadent). This was a patented material exclusively manufactured by Ivoclar Vivadent and is available in a pressable version (IPS e.max Press) or as a partially crystallized ceramic block (IPS e.max CAD) for computer-aided design and computer-aided manufacturing (CAD / CAM). Unlike its predecessor, Empress 2, which could only be used as framework material, the pressable and machinable version of IPS e.max can be used in a monolithic form. The availability of this relatively translucent high-strength monolithic ceramic material combined with the emerging demand for metal-free restorations is probably why the use of lithium disilicate restorations is so widespread (Christensen *et al*., 2011).

In a systematic review Pieger *et al*., (2014) analysed the short-term (one to five years) and medium-term (five to ten years) survival rates of lithium disilicate single crowns and partial fixed dental prostheses. An overview of the results obtained in the clinical studies carried out on this material is provided in Table 1. Only a few crown fractures occurred, if any at all. For lithium disilicate single crowns, the short-term evidence (one to five years) indicates an excellent cumulative survival rate (CSR) with a 2-year CSR of 100% and a 5-year CSR of 97.8%. The evidence for medium-term survival (five to ten years) is limited, with data from only one study contributing to a 10-year CSR of 96.7%. Most single crowns failed in the posterior region (Pieger *et al*., 2014).

In addition to its use for single crowns, the inherent strength of the material has seen it being used more widely in a minimally invasive, partial restoration protocol (Rocca *et al.*, 2015). The pleasing physical properties of lithium disilicate have a significant impact on the underlying preparation design, supporting the development of ultra-conservative preparation protocol (Silva *et al.*, 2012; Valenti, 2015). These developments and their impact are discussed in detail at a later stage in this thesis

Table 1: Intact crowns and fractured crowns reported in clinical studies of up to 45 months to evaluate IPS e.max CAD (adapted from Pieger *et al.*, 2014)



Monolithic composite restorations

In addition to glass ceramic restorative material, new monolithic composite resin blocks have also become available. These resin materials such as Lava Ultimate, (3M) and Enamic (VITA) can be used in the CAD / CAM restorative process. These monolithic composite resin blocks have the added advantages that they can be repaired in the mouth (Rocca et al.

2010). Recent *in vitro* studies on the fracture and fatigue resistance of direct and indirect restorations used in the treatment of severely eroded teeth, demonstrated that these monolithic resin materials have very favourable properties (Hamburger *et al.*, 2014; Schlichting *et al.*, 2016). This has seen the increased use of bonded monolithic composite resins for the treatment of severe wear (Schlichting *et al.*, 2016). However, these initial results necessitate further investigation.

1.2 CAD / CAM processing in dentistry

In an attempt to achieve minimum thickness in ceramic restorations, it is important to follow a process that produces the strongest possible material. When choosing between monolithic and bilayer ceramic, it is important to note that the layering porcelain that is stacked over the core of all restorations produces flexural loads of between 90 and 140 MPa (Taskonak, Mecholsky and Anusavice, 2005). This could lead to weakening of the system in the narrow available space. Within the confines of producing restorations of minimal material thicknesses monolithic restorations should therefore be the first choice.

An increasingly popular method for manufacture and processing such monolithic indirect restorations is through the use of CAD / CAM technology. CAD / CAM is an acronym for Computer Aided Design / Computer Aided Manufacturing. The technology of Computer-Aided Design (CAD) makes use of computer systems to assist in the creation and modification of a design for further Computer Aided Manufacturing (CAM).

Dr Francois Duret was the first to develop a dental CAD / CAM device, known as the Sopha System (Sopha Bioconcept, Inc. USA). However, due to its high cost and complexity of use, the device was unsuccessful in the dental market. In the early 1980s, Dr Mörmann and his team succeeded in developing the first dental chairside CAD / CAM system, known as the CEREC system (Mörmann, 2004). A digital impression of an inlay prepared cavity was performed using an optical intra-oral camera. The digitised data was used to design and fabricate the first single visit chairside CAD / CAM inlay restoration. During the same period, a CAD / CAM technology for fabricating composite veneered restorations was introduced. This system was later known as the Procera System (Andersson & Odén, 1993). Since then, many different systems have been introduced to the dental market.

The components of dental CAD/CAM systems

Every developed dental CAD / CAM system is composed of three basic components: scanner, design software and processing device (Beuer *et al*., 2008).

Scanner

The scanner is a critical component of any dental CAD / CAM system, since the accuracy of the design is limited by the accuracy of the captured and imported data (Fasbinder, 2010). A digital scanner collects three-dimensional data of the prepared teeth, neighbouring structures and opposing teeth, either intra-orally or extra-orally from cast models. Following image acquisition, the final data is either used for chairside fabrication of restorations or digitally transmitted to a laboratory. Today, there are many different scanning devices available. The most widely used is the optical scanner, in which a laser or white light source is used based on a triangulation procedure to capture several static or video images of the prepared tooth surfaces (Beuer *et al*., 2008). Examples of this system include CEREC, Lava Scan, and Everest Scan.

Design software

Design software are software programs that are used for the visualisation of the scanned data and the planning and designing of 3-D dental restorations. A variety of dental restorations can be designed, including inlays, onlays, single crowns, copings and fixed dental prostheses. Software engineer Alain Ferru, in cooperation with Mörmann, designed the first dental software ref. Using the anatomy of natural teeth and the collected intra-oral preparation data, the CEREC 1 software was able to design the first chairside CAD / CAM inlay restoration (Mörmann, 2006). The design was displayed two-dimensionally. With the subsequent development of CEREC 2 software in 1994, the dentist was able to design and fabricate full crown restorations and copings. However, the design was still displayed in a 2-D format. Partially due to recent improvements in computer speed and memory, the CEREC 3, with its

3-D capability, was introduced in 2005 (Fasbinder, 2010). This generated 3-D data can be transformed into various data formats. Recently, CEREC AC, powered by Omnicam, was introduced to the market. This system provides the advantage of powder-free scanning and a wide indication spectrum and allows for the chairside fabrication of inlays, onlays, veneers, single crowns, bridges and surgical guides.

Processing devices

Virtual restorations provided by CAD software systems are converted to dental restorations using computer-controlled milling devices. A variety of prefabricated material blocks, such as ceramics, composites and metals can be machined in different axes to produce the desired restoration. The final correction, polishing and staining is carried out by the dental technician or dentist. Two processing CAD / CAM systems are defined below.

- **Chairside system**

  With this system, all the components of the CAD / CAM process are located in the dental office. Different dental ceramic material blocks for chairside milling are available. There are many chairside systems available in the dental market. The CEREC system is the most widely used and is well documented. CEREC AC (Sirona dental system, Bensheim, Germany), the newest version of CEREC, provides the ability to fabricate chairside dental restorations in one visit. Through the Sirona digital network (CEREC Connect) the optical impression can also be sent to the dental laboratory via email.

- **Lab-side system**

  With a lab-side system, all the components and production steps of a CAD / CAM system are located in the laboratory. The 3-D data can be generated using a conventional dental impression and master cast, which is later digitally scanned, or, alternatively, chairside digitally scanned data can be sent or emailed from the dental office to a laboratory. Many of the lab-side systems, such as Lava (3M ESPE, St. Paul, USA), Everest (KaVo, Biberach, Riss) and Cerec InLab (Sirona, Bensheim, Germany), produce monolithic restorations and copings and frameworks, which later require veneering with either manual or CAD / CAM techniques.

1.3 Adhesive cementation

A further critical aspect of “minimally invasive” dentistry is the ability to adhesively bond the chosen restorative material to the underlying tooth structure. The role of the adhesive cement is to act as the link between the restorative material and the underlying tooth, creating a synergy between restoration and tooth. Such a link is based on three key components:

- The choice of luting agent
- Adhesion to the tooth structure
- Adhesion to the restorative material

1.3.1 Choice of cements

The character of cementation has evolved over the course of the century; from its primary use as a sealer, intended to fill the space between the restoration and the tooth, to its current use as luting agent that adhesively bonds indirect restorations (Larson, 2013).

With the increased use of full porcelain restorations in a continually evolving profession, there has been a greater need for cementation techniques and materials that allow for predictable bonding of ceramics to the tooth structure. Resin-modified glass-ionomers, resin cements and, most recently, self-etching adhesive resin cements have been introduced to improve physical properties and move closer to an ideal luting material (Larson, 2013).

Classification of cements

The literature varies considerably on the classification and discussion of cements. Craig (1998) followed a traditional method of classifying cements according to their main ingredients (i.e. zinc phosphate, zinc oxide-eugenol, glass-ionomer, and resin), whereas O'Brien (2002) classified dental cements by matrix bond type (i.e. phosphate, phenolate, polycarboxylate, resin, and resin-modified glass-ionomer).

A simplified classification, discussed by Vargas *et al*., (2011), uses the primary cementing procedures as reference. These can be adhesive or non-adhesive. Adhesive cementation involves the use of an agent to promote bonding of the restorative material to the substrate and is a combination of adhesive chemical bonding and micromechanical interlocking. Non-adhesive cementation involves the use of a luting agent to fill the space between the restoration and the natural tooth, and relies solely on micromechanical retention.

The modern dental luting agents are also often referred to as "cements", even though they are completely different from the original cements and feature different chemical curing mechanisms. Phosphate cements, polycarboxylate cements and glass ionomer cements are considered classic cements and belong to the group of "dental water-based cements". Modern luting composites are resin-based cements that can be subdivided into two groups, namely; self-adhesive resin cements and adhesive luting resins (Vargas, Bergeron and Diaz-Arnold, 2011).

Self-adhesive resin cements

In recent years, phosphate-monomer containing self-adhesive resin cements have been developed and commercialized. Examples of self-adhesive cements include RelyX Unicem (3M ESPE) and MaxCem (Kerr). These self-adhesive cements can bond to an untreated tooth surface that has not been micro-abraded or pre-treated with an etchant, primer, or bonding agent. Thus, cementation is accomplished in a single step.

Data from Burgess *et al*. indicates that most of these cements bond better to dentine than to enamel (Burgess *et al*., 2010). With most of the cements in this category, the bond to enamel is improved when an etchant is applied. 'Selectively etching' enamel may be incorporated to improve the bond of these self-adhesive resin cements (Burgess, Ghuman and Cakir, 2010).

It is important to note that, compared to traditional resin cements; self-adhesive resin cements usually have weaker physical properties, are more hydrophilic and have higher water sorption (Chen, 2012). D'Amario (2010) further showed that the bond strength of self-adhesive cement RelyX UniCem (3M ESPE) and Multilink Automix (Ivoclar, Schaan) was significantly affected by thermo-cyclic aging, compared to traditional resin cements (D'Amario *et al.*, 2010). Clinicians should therefore carefully consider the use of self-adhesive resin cements and the clinical situation they are to be used in.

The separate use of a bonding agent is not recommended with self-adhesive resin cements. Although bonding agents may be compatible with self-adhesive resin cements, their use makes the manipulation more complicated and does not dramatically improve bond strength to tooth structure. Higher bond strengths to tooth structure can be obtained with aesthetic resin cements that are bonded with separate bonding agents (Powers *et al*., 2009).

Adhesive resin cements

In order to obtain a strong bond between the tooth structure and the restoration, adhesive-luting composites are used in combination with dental adhesives. The adhesive is able to create a strong bond to varying substrates ranging from dentine, enamel, composite, and combinations of these. The clinical steps and long-term stability of this bond is dependent on the adhesive technique of choice; whether it be the "total-etch" or "self-etch" technique. The merits of both these techniques are discussed in the section relating to the use of adhesives.

The luting agents in turn form a chemical bond with the adhesive, thereby generating a particularly strong bond to the tooth structure. Adhesive luting permits bonding in situations where no large retentive surfaces are prepared. An adhesive bond increases the fracture resistance and thus the survival rate of all-ceramic restorations. Minimally invasive restorative techniques, such as non-retentive occlusal veneers, would be unthinkable without adhesive luting composites (Vargas *et al*., 2011).

Resin cements have compositions and characteristics similar to conventional restorative composites and consist of inorganic fillers embedded in an organic matrix. These cements can generally be classified according to their mode of setting (polymerization).

Resin cement polymerization

Polymerization of resin cements can be achieved through the use of light, chemicals, or a dual process that combines the two. Light-polymerized resins (LC) are recommended when the ceramic is thin and fairly translucent, allowing the transmission of light, through the ceramic so that it can reach the resin cement. Dual-polymerized resin (DC) cements are indicated when the ceramic is too thick or too opaque to allow the transmission of light through it. Chemically polymerized resin cements do not offer much selection in terms of shade and translucency (Blatz and Sadan, 2003). Their use is therefore limited.

Light-cure resin cements utilize photo-initiators, which are activated by light. The ability of light to penetrate all areas and activate the photo-initiators is important with this type of cement. It is generally accepted that light-cure resins require 400 mW/cm^2 of light intensity for 20 seconds of exposure to generate the 8000mJ of energy that ensures proper polymerization (hardening) (Price, 2014). Two examples of light polymerized cements are

RelyX™ Veneer Cement (3M ESPE, USA); and Variolink® Veneer (Ivoclar Vivadent Inc.). Dual-cure (DC) resin cements are capable of being cured by means of both light and chemicals through the presence of self-cure initiators. Examples include RelyX™ ARC Adhesive Resin Cement (3M ESPE); and Variolink® II (Ivoclar Vivadent Inc.).

In the use of DC cements, it may be assumed that the chemical component of the cement may compensate for the decreased light transmission. It has, however, been demonstrated that the chemical component of DC resin cements alone cannot sufficiently enable maximum monomer conversion, and exhibit significantly better flexural strengths and modulus of elasticity when it is cured with light-curing (Larson, 2013).

In a study conducted by Kilinc (2011). the effect of ceramic thickness on light intensity transmitted through the ceramic was tested. only the 1mm-thick ceramic allowed 400mW/cm^2 of light transmission on to the cement surface. In ceramics of 3mm to 4mm, light transmissions were as low as 60mW/cm^2 (Kilinc *et al*., 2011). In his conclusion, Kilinc stated that the resin groups cured through thicker ceramics were possibly far from reaching adequate energy levels, and contributed to the approximately 60% to 70% decrease in micro hardness values, compared to their control group (Kilinc *et al*., 2011). The results show that ceramic thickness has a major effect on light transmission and the subsequent micro hardness of DC and LC resins.

Table 2: Advantages and disadvantages of light cure (LC) and dual cure (DC) resin cements.(Vargas, Bergeron and Diaz-Arnold, 2011)

	ADVANTAGES	DISADVANTAGES
LC	• dentist decides when curing starts, resulting in more time for inserting restoration (working time) • no chemical initiators with tendency to discolour • excess removal can be triggered by short light impulse	• light must reach composite • not suitable for opaque and thick restorations
DC	• sufficient polymerization where light does not reach completely • excess removal can be triggered by short light impulse	• light should reach the composite • chemical initiator might have tendency to discolour

The decision to use DC or LC cement also greatly impacts the bonding protocol followed. When using DC resin cements, most manufacturers require the use of a separate activator to aid in the polymerisation of the adhesive. It is important to note that investigators have found incompatibilities between some dual-cure resin cements and simplified “universal” adhesive systems (Vargas *et al*., 2011). It is therefore critical for clinicians to understand the adhesive system used and its impact on the cements’ performance.

1.3.2 The use of adhesives

When using resin cements, the resin cement is adhesively bonded to the underlying tooth structure. This bond can be achieved by using a total-etch, self-etch or universal adhesive system (see table 3). The 4th generation total-etch three-step adhesive system (RelyX ARC, 3M ESPE; Variolink II, Ivoclar Vivadent Inc) is considered to be the gold standard (Van

Meerbeek *et al.*, 2003). These multi-step application techniques are however, complex and might compromise bonding effectiveness as each step represents a possible contamination point (Scotti *et al.*, 2017).

Generation 5 and 6 self-etching systems have become increasingly popular among clinicians, due to their ease of use (Scotti *et al.*, 2017). Self-etch systems apply a self-etching primer to prepare the tooth surface and mixed cement is then applied over the primer. The bond strength to tooth structure using these cements are as high as those of the total-etch cements but, in general, they have demonstrated bond strength to enamel that is weaker than that of total-etch systems (Van Meerbeek *et al*., 2003).

Seventh generation universal adhesives appeared on the market in 2011. This new (largely 1-step) adhesive category helps simplify the bonding procedures. It offers products that can be used with all etching protocols, for direct and indirect bonding procedures (Wagner *et al.*, 2014).

Classification of adhesive systems

Whilst the generational system of classification is helpful for looking at adhesives from a historical perspective, it may be more meaningful to classify them according to how they work and how many working steps are involved (see table 3).

Modern dental adhesives can be classified into two basic types: etch-and-rinse and self-etch adhesives (Sofan *et al.*, 2017). Etch-and-rinse systems comprise of phosphoric acid to pre-treat the dental hard tissues before rinsing and subsequent application of an adhesive. Although the etch-and-rinse term is often used synonymously for total-etch adhesives, theoretically it covers both total-etch and selective-etch adhesives. In other words, in total-etching, both enamel and dentine are etched and rinsed; while in selective-etching, only the enamel is etched and rinsed. These systems can then be sub-categorized based on the number of clinical steps involved. The etch-and-rinse systems can be classified as being multi-step, three-step or two-step, while the self-etch systems can be classified as being either two-step or one-step.

The etch-and-rinse system is distinct in that it has a separate etch-and-rinse step prior to the priming and bonding steps (Sofan *et al.*, 2017). The three-step etch-and-rinse / total-etch system (using fourth-generation adhesives) follows the conventional "etch-rinse-prime-bond" approach. The two-step etch-and-rinse system (using fifth-generation adhesives, also known as one-bottle adhesives) combines the primer and the bonding agent into one application. The self-etch adhesive system eliminates the rinsing phase after etching by using non-rinse acidic monomers to etch and prime dentine simultaneously. The two-step self-etch system (involving sixth-generation adhesives) uses acidic monomers as self-etch primers in the initial step and an adhesive resin in the second step. The one-step self-etch system (using seventh generation adhesives, also known as all-in-one adhesives) combines the (self-etch) acidic primer with the adhesive resin in one application step. This allows for simultaneous infiltration of adhesive resin to the depth of demineralization, which may reduce postoperative sensitivity. The universal adhesives differ in terms of their claimed universality. However, in general they too combine the acidic primer with the adhesive resin in one step, and can be used with all etching techniques, making them suitable for use with both direct and indirect restorations.

Table 3: An overview of the current adhesive systems commercially available. (Sofan *et al.*, 2017)

This overview classifies the adhesives according to their mode of application instead of the more traditional generational classification.

Etch & Rinse	Selective-Etch/Multi-step	Selective enamel etch/etch-and-rinse. Dentine conditioning with primer to modify or remove smear layer
	Total-Etch/Multi-/3-step	Total-etch/ etch-and-rinse; separate primer and adhesive
	Total-Etch/ 2-step	Total-etch/ etch-and-rinse; combined primer and adhesive
Self-Etch	Self-Etch/ 2-step	Self-etch; etch and primer combined but hydrophobic bonding agent separate
	Self-Etch/ 1-Step	Self-etch; etch, primer and adhesive combined
All-Etch	Total-/Self-/Selective-Etch/ 1 or 2 step	Total or selective etch procedure followed by universal adhesive or use of universal adhesive only in self-etch mode

Self-etch adhesives

The development of new dentine bonding materials has stemmed from a desire to minimise the number of steps involved during the bonding procedure. Self-etch adhesives contain acidic monomers, which allows for the simultaneous etching and priming of dentine. This allows for a reduction in the steps needed for effective dentine bonding. Self-etch adhesives are available as one- or two-step systems.

Besides being simpler and less technique-sensitive, self-etch adhesives are claimed to have other advantages, one of which is reduced post-operative sensitivity. This is due to residual smear plugs being left in situ, thereby exposing less dentinal tubules and causing less dentinal fluid flow than the traditional etch-&-rinse bonds (Hashimoto *et al*., 2004).

The varying evidence available today suggests that the choice between etch-and-rinse and self-etch systems is often a matter of personal preference (Ozer and Blatz, 2013a). In general, however, phosphoric acid creates a more pronounced and retentive etching pattern in enamel. Conversely, self-etch adhesives provide superior and more predictable bond strength to dentine and are, consequently, recommended for direct composite resin or restorations that are predominantly supported by dentine (Ozer & Blatz, 2013). When using self-etch adhesives, it is recommended to use selective enamel etching to create a more pronounced enamel-etching pattern, thereby increasing the final bond strength (Rosa *et al*., 2015).

It is important to note, when using self-etch adhesives in combination with composite luting cements, that while self-etch adhesives may yield acceptable results when applied in combination with light cured composite luting cements, their acidic monomers inhibit the polymerization of auto-cured and dual-cured composite luting cements (Haller, 2013). Unfortunately, most “self-cure” or “dual-cure” activators do not overcome this problem. This incompatibility has to be taken into consideration when using self-etch adhesives for adhesive cementation and for core build-up restorations.

Universal adhesives

Universal adhesives appeared on the market in 2011. This new (largely 1-step) adhesive category simplifies bonding procedures, offering products that can be used with all etching protocols. It can be used for direct and indirect bonding procedures (Wagner *et al.*, 2014).

These "universal adhesives" are designed under the ‘‘all-in-one’’ concept of the already existing one-step self-etch adhesives but, also incorporates the versatility of being adaptable to the clinical situation. Its versatility lies in its ability to be applied both as etch-and-rinse or self-etch, providing the practitioner with the choice for the specific adhesive protocol that is best suited to the cavity being prepared (Wagner *et al.*, 2014).

Although recent studies reported that universal adhesives applied using either the etch- and-rinse or the self-etch mode produce excellent immediate bond strength to various bonding substrates (Wagner et al. 2014), the durability of bonds produced by these adhesives are similar to that of multi step procedure (Masarwa *et al.*, 2016). Some manufacturers have incorporated 10-methacryloyloxydecyl dihydrogen phosphate (10- MDP) into their adhesives as a means of chemical bonding to apatite via nanolayering of 10-MDP-calcium salts in an attempt to create more stable bonds (Van Meerbeek *et al.*, 2003). In a 2016 study, Zhang concluded that bonds created by the five tested universal adhesives in the self-etch mode are, in general, more durable than those created in the etch-and-rinse mode (Zhang *et al.*, 2016). These factors should be taken into consideration when deciding on clinical protocol that would achieve long term stability of indirect restorations that are bonded using "Universal" adhesives.

It is important to note that, as with all self-etch adhesives, selective enamel etching could be considered the best strategy for optimizing the bond strength of universal adhesives (Rosa *et al.*, 2015).

Bonding to restorative composite

Using resin composite in combination with indirect porcelain restorations helps provide additional reinforcement when a tooth shows excessive loss or damage. This has seen techniques such as Cavity Design Optimization (CDO) and Cervical Margin Elevation (DME) becoming increasingly popular amongst clinicians (Dietschi & Spreafico, 2015). With these techniques there is an increased need to bond ceramics to restorative composite.

In clinical practice, bonding between two composite layers is accomplished by the presence of an oxygen-enriched surface layer that remains un-polymerized. This layer contains unreacted C=C bonds, allowing the monomers of the new composite resin to bond to it. When bonding to aged composite resin, the adhesion reduces to between 25% and 80% of the original cohesive strength. This is due to a diminished amount of unreacted double bonds (Özcan *et al*., 2007). The successful bonding of new-composite resin to old-composite-resin is dependent on the following factors: the chemical composition of the surface; surface roughness; wetting and the surface conditioning methods applied (Özcan *et al*., 2013).

The success of modern preparation techniques such as CDO and DME is dependent on the reliability of the bond that can integrate all parts of the system, including composite resins, luting cement, and ceramic. Gresnigt (2012) investigated the impact of aged composite cores on the performance of the adhesive cements. They concluded that aging of composite did have an impact on the final bond strength and durability of the restorations (Gresnigt *et al.*, 2012), recording bond strengths as low as 12.8N. Showing the significant impact that aged composite can have on the final bond strength.

To achieve a stronger and more predictable bond between these components, a number of mechanical and chemical surface treatments have been developed. A recent study suggest that treatment with air abrasion, followed by silane application, is an effective method for preparing the aged composite core surface for bonding to resin cement (Ahmadizenouz *et al*., 2016). Clinicians should therefore take into consideration the impact of the aged composite restorations during the preparation protocol and follow the necessary processes during cementation to achieve long-term success.

When using CAD/CAM chair side technology, the clinician has the ability to prepare, manufacture and bond definitive restorations in a single visit. Allowing the adhesive cement to be bonded to fresh restorative composite, avoiding the problem of aged composites. This could have a direct influence on the strength of the adhesive bond and the durability of the final restoration.

1.4 Adhesion to silica based ceramics

The adhesive resin should not only form a strong bond with the underlying tooth structure or restorative composite, but should also from a lasting bond with the ceramic intaglio. Such a bond is dependent on both the clinical steps followed and the properties of the ceramic material being bonded to (see table 4). It is therefore important that the clinician takes the properties of the ceramic intaglio into consideration when making the treatment choice.

When bonding to the ceramic intaglio, the clinical steps and material choices vary, but follow similar methods (Larson, 2013).

(1) **Surface treatment**: The intaglio surface must be roughened, by etching with a hydrofluoric acid or sandblasting, or both.

(2) **Ceramic primers**: Application of a ceramic primer is required for some porcelain so that the resin luting material can polymerize with the glass particles of the restoration material.

Table 4: Ceramic surface treatment according to ceramic type (adapted from Vargus *et al.,* 2011)

Each treatment process differs according to the ceramic type and filler used.

CERAMIC	FILLER	SURFACE TREATMENT
Predominantly Glass	Aluminium Oxide	10% HF Acid for 1 minute, rinse and dry; apply silane for 1 minute and dry
Particle Filled Glass	Leucite	Apply 5% HF for 1 minute, rinse and dry; apply silane for 1 minute, dry
	Lithium Disilicate	Apply 5% HF for 20sec, rinse and dry; apply silane for 1 minute, dry
	Glass infiltrated alumina	Perform air abrasion with aluminium oxide or tribochemical silica coating, apply adhesion promoting agent containing MDP and dry
Polycrystalline	Aluminium Oxide	Perform air abrasion with aluminium oxcide, apply adhesion promoting agent containing MDP and dry
	Zirconium Oxide	Perform air abrasion with 50 micron aluminium oxcide, apply adhesion promoting agent containing MDP and dry

Surface treatment

A strong resin bond to the ceramic surface relies on micromechanical interlocking and chemical bonding (Blatz and Sadan, 2003). Common treatment options include grinding, airborne particle abrasion with aluminium oxide, acid etching, or combinations of any of these methods. Table 4 gives an overview of the surface treatment advocated for varying restorative materials.

For the glass ceramics which contain various amounts of glass / silica, such as lithium disilicate, etching with 4-9.5% hydrofluoric acid has proven a successful surface treatment method (Blatz and Sadan 2003). The application of a diluted hydrofluoric acid dissolves the silicon ions thereby forming a retentive pattern. Silicon has a high chemical affinity to fluoride ions. The formed silicon fluoride derivatives are soluble and can be rapidly washed off with water. This step provides an increased surface area, micromechanical retention and a clean surface.

Unfortunately, hydrofluoric acid is a very strong poison (Özcan *et al*., 2012), even in the dissolute state. It is a weak acid and can burn the skin. After penetrating, it moves quickly into deeper tissue layers and releases the freely dissociable fluoride anion. Fluoride is very toxic due to its high cellular deaths and necrosis. Skin contact with HF acid can cause painful burns that take a long time to heal. Latent damages can also be observed since the fluoride ions penetrate through all layers of the epidermis, resulting in necrosis or injuries to the underlying bone due to decalcification (McKee *et al.*, 2014).

Ceramic primers

Primers improve bonding between resin cements and various restorative materials. They can be classified based on the substrate (silica-based ceramics, alumina, zirconia, or alloy) for which they are intended (Vargas, Bergeron and Diaz-Arnold, 2011). Silanating primers are used with silica-based ceramics (feldspathic porcelain, leucite reinforced ceramic, lithium disilicate ceramic). Application of a silane coupling agent to the pre-treated ceramic surface provides a chemical covalent and hydrogen bond (Figures 3) and is a major factor in the formation of a strong bond between the resin and the silica based ceramic (Blatz and Sadan, 2003). Silane methacrylate is the reactive agent that forms the strong chemical bond with the composite matrix during curing.

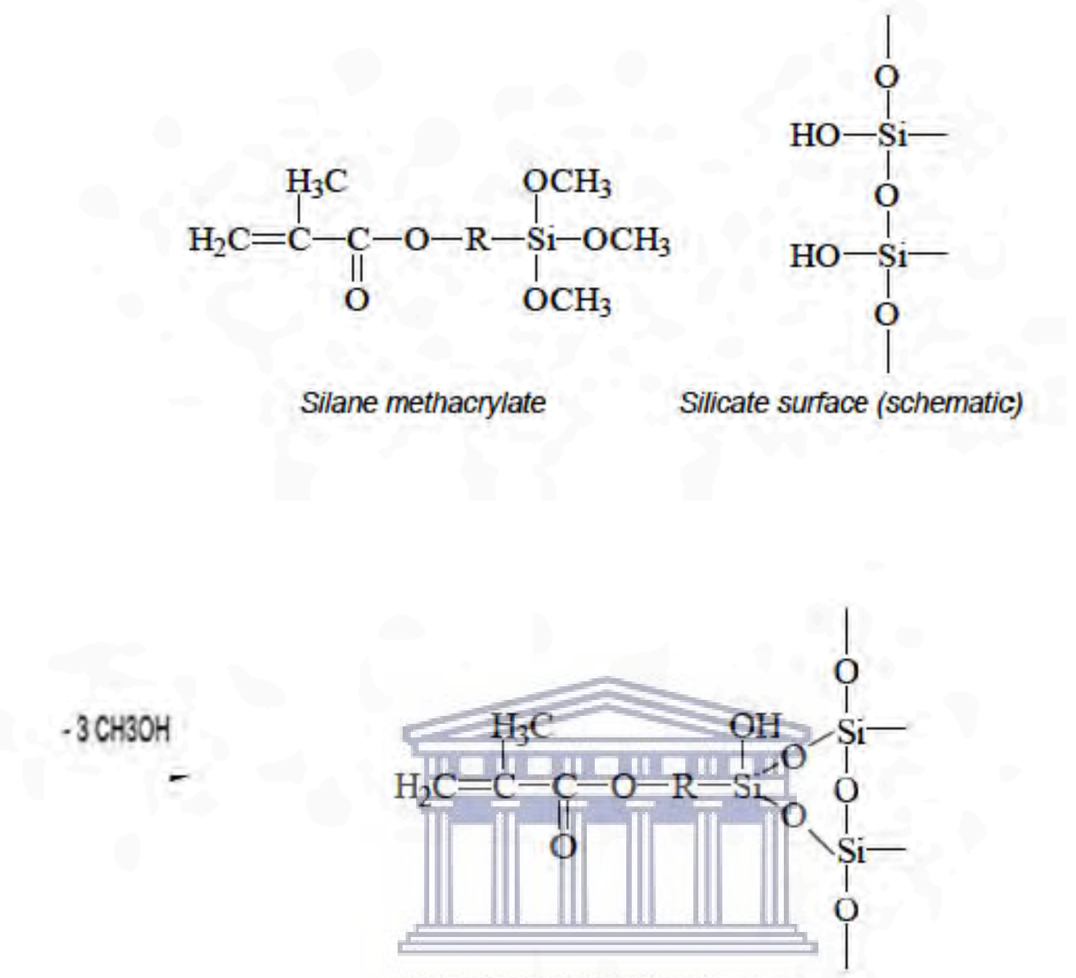


Figure 3: Schematic representation of the silanisation reaction mechanism (Lung and Matinlinna, 2012)

Hydrolysed silanes are most commonly one-bottle systems with a short shelf life. Unhydrolysed or “inactive” silanes are two-bottle systems that are mixed before application, to ensure a fresh and active solution (Lung and Matinlinna, 2012).

Sorensen (1991) showed that ceramic etching and silanisation significantly decrease micro-leakage, which was not achieved with the exclusive silane treatment of silica-based ceramics.

Monobond etch and prime

Monobond etch and prime (ME&P - Ivoclar Vivadent, Schaan, Lichtenstein) is a novel single bottle ceramic primer that allows for etching and silanisation of the glass ceramic surface in one step. It contains a trimethoxypropyl methacrylate for silanisation and a new ammonium polyfluoride for the etching step. The etching creates a roughness pattern, which is less pronounced than that found with HF gel, but is as efficient for bonding (Völkel and Braziulis, 2015).

Ammonium polyfluoride reacts with the silicon on the glass ceramic without the release of HF. This is due to the high chemical affinity between the silicon and fluoride. After the extra-oral application, the remaining liquid is thoroughly rinsed off. Once dry, a thin silane layer of molecular scale remains on the luting surface. This reacts via the methacrylate group with the luting composite during curing (Völkel and Braziulis, 2015).

During in-house studies, the bond strength of Monobond etch-and-prime bonded to various ceramic substrates was evaluated (Völkel and Braziulis, 2015). Monobond etch and prime produced a high aging-resistant adhesive bond on various ceramic materials. These were similar to that produced by the silane agent Monobond Plus after hydrofloric acid etching. Additionally, similar bond strength values on IPS e.max CAD with both Monobond Etch & Prime and Monobond Plus were achieved (Völkel & Braziulis, 2015).

The cytotoxicity of Monobond Etch & Prime was tested *in vitro* according to ISO 10993-5 ref. Monobond Etch & Prime is water soluble and only showed a cytotoxic effect on the L929 cell line examined when applied in very high concentrations (Völkel & Braziulis, 2015). Given that ME&P is applied only in small amounts at a time and the application procedure is performed extra-orally, the cytotoxic risk of ME&P is very low for the patient and user (Völkel & Braziulis, 2015).

1.5 Preparation design for all-ceramics

Once a clinician has decided on the material of choice, the cavity design becomes a major factor influencing the fracture resistance of the all-ceramic restoration. The volume of the restorative space created determines the thickness of the restorative ceramic which influences it subsequent strength. This is of great importance as Naeselius *et al*. (Naeselius, Arnelund and Molin, 2008) have shown that partial or total fracture was still the most frequent cause of ceramic restoration complications. Catastrophic fracture or bulk fracture is often seen as the main causes of failure in posterior-tooth restorations (Krämer *et al.,* 2005). This applies to both the older ceramic systems as well as the more recent ones.

Certain cavity designs can contribute to the reduction of the physical stresses within the restorations, thereby increasing the load strength and reducing the risk of fracture (see Figure 4) (Arnetzl and Arnetzl, 2009). These include:

- Semi-spherical cavity floor segments and rounded cavity shapes
- Rounded preparations with no sharp angles
- Avoiding of acute angles in the restoration material
- Maintaining a minimum thickness of the ceramics

Preparation protocol

- Hemispherical cavity floor and rounded shapes
- no sharp internal angles
- avoid acute angles in restoration materials
- maintain the minimum thickness ceramic

Figure 4: Current preparation protocol as advocated by Arnetzl & Arnetzl (2009)

1.5.1 Revised approach to cavity design

The revised approach to cavity design aims to alleviate most complications encountered in indirect posterior restorations. In this approach, direct restoratives are used in combination with ceramics, to optimize the cavity design and geometry, thereby increasing the ceramic strength and reducing complications (Dietschi and Spreafico, 2015). Some of these techniques include:

- Cavity Design Optimization (CDO)
- Cervical Margin Relocation (CMR)

Cavity Design Optimization (CDO)

CDO was developed in parallel with Immediate Dentine Sealing (IDS) to overcome the unnecessary removal of tooth structure when designing indirect restoratives (Magne, 2005). Following the application of the dentine bonding adhesive (DBA) according to the IDS concept, a flowable composite liner is applied to fill in all undercuts and create ideal cavity geometry (Figure 5). The material used should ensure stability within the undercuts, while being self-levelling to avoid further preparation and finishing. For this reason, highly filled flowable composites are recommended.

In this way, not only is the unnecessary removal of otherwise over-hanging tooth parts avoided, but it is also assured that the material thickness of the later indirect ceramic restoration remains as uniform as possible (Ahlers *et al.*, 2009). When one takes into consideration the necessary energy for light polymerization under the ceramic restoration, this procedure is also helpful in creating an additional measure of certainty that adequate polymerisation of the adhesive cement will take place (Price, 2014). Figure 7 shows a clinical situation where CDO was used to create the ideal preparation design.

Preparation protocol

Application of an adhesive base liner using CDO:

- Reinforces tooth walls & fill undercuts
- Optimise cavity geometry & leveling
- Consistent restoration thickness

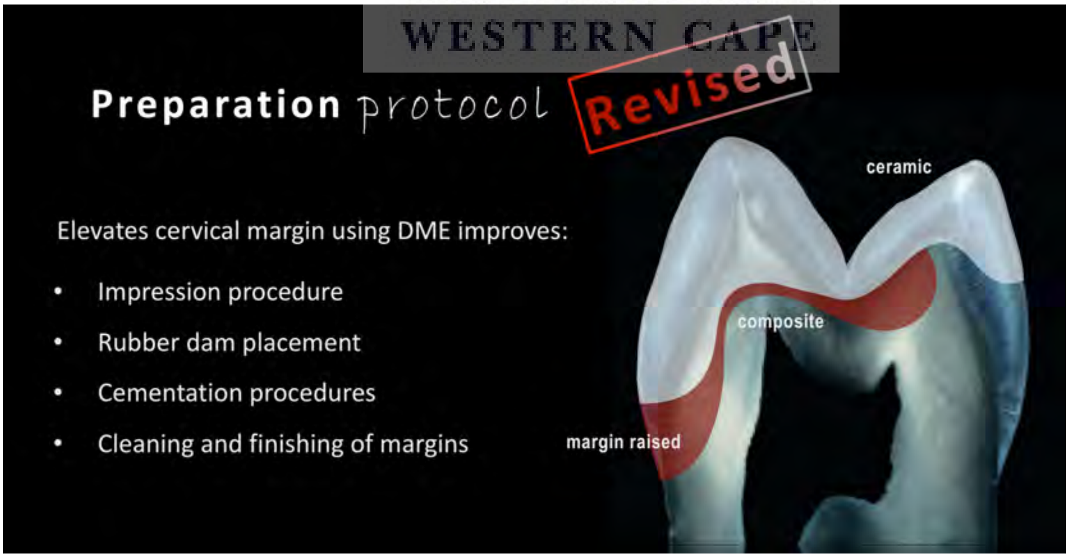
Figure 5: Cavity design optimisation (CDO) – as proposed by Dietschi (1998).

The application of an adhesive base liner (blue) using composite restorative materials is used to optimise the preparation design.

Cervical Margin Relocation (CMR)

Cavity Margin Relocation (CMR) was also introduced by Dietschi and Spreafico (Dietschi & Spreafico, 1998) and renamed Deep Margin Elevation (DME) by Magne and Spreafico (Magne, 2005). The use of this technique is advocated in instances when deep proximal preparations could cause complicated impression taking or prevent cavity isolation during cementation Figure 6. In the case of deep proximal preparations, after proper positioning of a matrix in the cervical area and the application of an adhesive, a layer of flowable or restorative composite is applied to reposition the margin. The use of a flowable composite is recommended when an elevation of between 1 and 1.5 mm is required. If more material is needed, a combination of restorative and flowable composites is recommended (Dietschi and Spreafico, 2015).

Spreafico showed that the implementation of DME had no effect on the quality of cervical margins before and after thermo-mechanical cycling (Spreafico *et al.*, 2016). CDO and DME are often used in combination to create the ideal cavity geometry.



Preparation protocol

Revised

Elevates cervical margin using DME improves:

- Impression procedure
- Rubber dam placement
- Cementation procedures
- Cleaning and finishing of margins

Figure 6: Deep margin elevation (DME) as advocated by Frankenberg (2012). Restorative composite (red) is used to raise the ceramic–restorative interface during preparation. This eases the fabrication and cementation of the ceramic restoration

a) large amalgam filling that is damaged and needs to be replaced. Numerous cracks and secondary decay is visible

b) after initial removal of the old restoration a large amount of decay and unsupported tooth structure is identified.

c) all unsupported tooth structure and secondary decay is removed

d) bonded composite is used to create an ideal preparation design following the principles of CDO

Figure 7: Clinical situation where CDO techniques are used to create the ideal preparation design (Dr Jean van Lierop).

1.5.2 The role of the substrate being bonded to:

With the revised approach to cavity design, composite resin plays a far greater role during cavity preparation. This creates a larger variation of substrates that the indirect porcelain restoration will be luted to. These variations include different combinations of enamel, dentine and composite. When designing the indirect porcelain restoration, the clinician would need to consider the influence that these variations in the substrates will have on the final bond strength, fracture resistance and ultimate longevity of the ceramic restoration.

In the traditional cavity design, substrates that are present during adhesive cementation are those of enamel and dentine. In 2010, Clausen *et al* investigated the fracture resistance of two types of monolithic porcelains bonded to varying amounts of enamel and dentine (Clausen et al., 2010). Clinically, this is relevant in determining the impact that the depth of preparation designs has on the restoration's long-term success. He concluded that the volume of dentine and enamel did not influence the fracture resistance of the porcelain, but that the type of porcelain had a far greater impact.

When it comes to the revised approach of cavity design, the greater volume of restorative resin means that the clinician has to consider the strength of the bond achieved when luting the porcelain restoration to a resin substrate. As previously discussed, the author has found very few studies that investigate the bond strength of a luting resin to aged composite substrates during indirect restorations cementation. Techniques have however been identified that could help increase this bond (Ahmadizenouz *et al*., 2016). Furthermore, the use of chair side CAD/CAM technology has the advantage of bonding restoratives to fresh composite resin.

Sasse et al have showed during recent in vitro investigations of the fracture resistance of Lithium di-silicate, that high values of fracture resistance and high survival rates of restorations can be achieved when partly bonded to composite material (Sasse et al. 2015).

1.5.3 The Occlusal Veneer Design

As can be seen in the clinical situation found in Figure 7, the limited amount of residual tooth structure following caries removal may often necessitate the modification of the preparation to incorporate and “overlay” a compromised or weakened cusp. Unfortunately, there is limited information available on what the minimum thickness of the remaining cavity wall should be before considering including it in the preparation (Krifka et al. 2009a).

Krifka *et al* investigated the role that cavity wall thickness could play in the marginal integrity of ceramic inlays (CI) and partial ceramic crowns (PCC), and the crack formation in dental tissues (Krifka et al., 2009). They concluded that the remaining wall thickness of non-functional cusps of adhesively bonded ceramic restorations, especially ceramic inlays, should have a thickness of at least 2.0 mm to prevent crack formation and to avoid long term tooth fracture. Furthermore, a remaining cusp wall thickness of 2.0 mm may also reduce the marginal deficiency (especially for CI) seen at the dentine / luting agent interface (Krifka et al., 2009). In situations where less than 2mm of remaining wall thickness is present, covering the weakened cusps (using partial ceramic crown restorations) leads to a reduction in the deterioration of the adhesive along the margins and a decrease in crack formation (S. Krifka *et al.*, 2009).

In contrast to these recommendations, Rocca et al. advise on 1 mm as minimal wall width/thickness before reinforcement with composite resin during the adhesive resin lining of the cavity (Rocca *et al.*, 2015). They conclude: “occlusal coverage is recommended for cavity walls of 1 mm or thinner, while for “intermediate” thickness (1 to 2 mm), the occlusal context including tooth position, presence of parafunctions, and the kind of lateral guidance (canine or group guidance) should be taken into account when making the decision to use cusp coverage."

With such contradicted guidelines, a guarded conclusion can be made that the minimum thickness of the cavity wall should be no less than 1.0 mm, with the clinical situation and functional aspects playing a major role in the decision process. In situations where less structure is available, or where structures are at higher functional risk, partial ceramic crowns should be considered.

The axial wall dilemma

When the decision had been made to include the compromised cusp intro the restoration, the decision of the manner in which to incorporate the cusp should be considered. Traditional crown preparation techniques required the extension of the preparation margins along the entire long axis of the clinical crown (Figure 1). Seydler *et al*. investigated the fracture resistance of lithium disilicate crown restorations (IPS E.max CAD) using such a traditional crown design (Seydler *et al*. 2013). This study confirmed the belief that full ceramic crowns are relatively resistant to compressive forces, however, the higher tensile and shear forces experienced along the axial walls necessitates a larger wall thickness. They found the fracture loads for posterior lithium disilicate crowns with 0.5 mm wall thickness were too low (<500 N) to guarantee a low complication rate *in vivo*, whereas those crowns with 1.0 and 1.5 mm wall thicknesses showed appropriate fracture resistances (>600 N) (Seydler *et al*., 2013). It was therefore concluded that when axial wall extensions are required, an increased ceramic thickness with corresponding tooth structure removal is recommended to prevent premature restoration fracture. This traditional axial wall extension results in the clinician, again, sacrificing tooth structure in order to attain predictable long-term strength.

The advances in adhesive cementation have seen the development of conservative table-top designs with no axial extension. This allows for the forces to be contained in occlusal compression only (Guess *et al*., 2013). This concept is referred to as the "compression dome". To understand the principals of the compression dome design, one needs to look at both the biomechanics and biomimetics involved.

Concept of the compression dome

Milicich first described the compression dome concept in association with biomechanical function of enamel in 2000 (Milicich and Rainey, 2000). In this concept, a tooth essentially acts as a compression dome, with the enamel being in compression on top of the underlying dentine (Ford, Bush and Lawn, 2009). The transition point between the enamel and the dentine, the dentine-enamel complex (DEC), has a sigmoid curve to it. If one looks at a tooth in cross section, the DEC follows a pattern that is replicated across all the posterior teeth, being concave in the upper third, and convex in the lower cervical area (Figure 8) (Goldberg *et al.*, 2002). During load, the DEC and the structural adaptations in the dentine allow for transferring and minimizing of stress and the development of tensile forces (Wang and Weiner, 1998b).

Figure 8 also indicates the point at which the sigmoid contour changes. This is known as the inflection point. Joining the buccal and lingual inflection points will indicate the inflection plane. In the lower teeth, the inflection plane is canted lingually, while in the upper teeth, it is canted to the buccal. In premolars, the inflection point is further down the side of the tooth, and as we move posteriorly, it moves occlusally.

Occlusal to the inflection point, the enamel is like the dome of the Pantheon, and below this point it supports the compression dome like the walls of the Pantheon (Figure 9) (Milicich and Rainey, 2000). When radial stress is exerted on a dome (circumferential stress) a phenomenon described as "Hoop stress" occurs (Wang and Weiner, 1998). In the top zone of a dome, Hoop stress is compressive, changing over into tension. In the tooth, this changeover point corresponds to the inflection point (Wang and Weiner, 1998).

Once the enamel compression dome and supporting structures have been damaged or removed, the underlying dentine distorts under lateral compressive forces causing the enamel at the marginal ridges to be placed under tension and creating vertical fractures which most commonly leads to the loss of a cusp (Milicich, 2017).

Bonded restorations give significant support to the tooth function and distribution of forces contributing to the prevention of fracture propagation (Tirlet *et al.*, 2014).The goal of partial coverage crowns or occlusal veneers should therefore be to recreate the lost compression dome and to protect the underlying dentine from tensile forces (Figure 10).

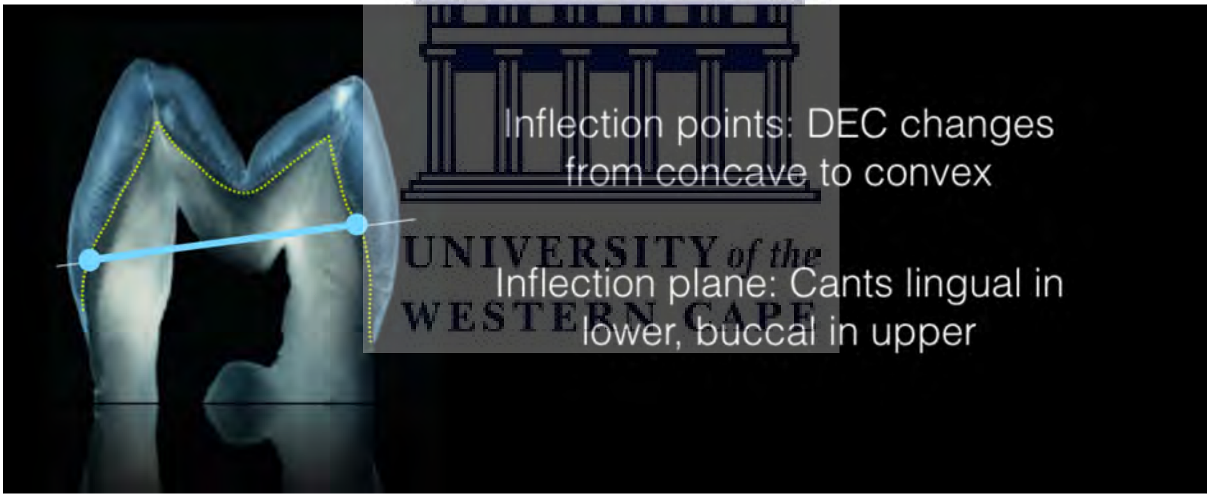
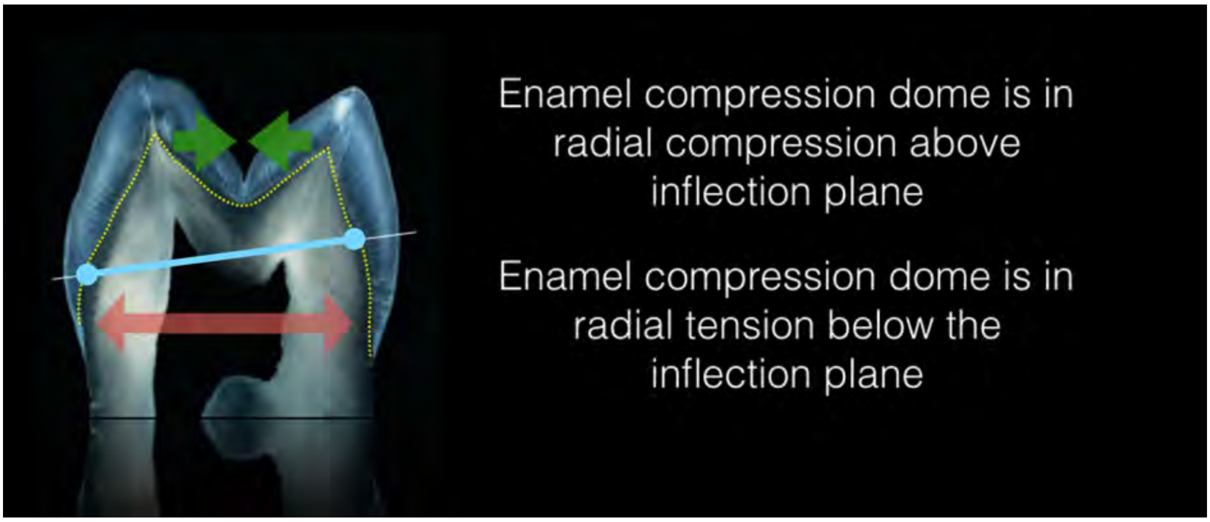


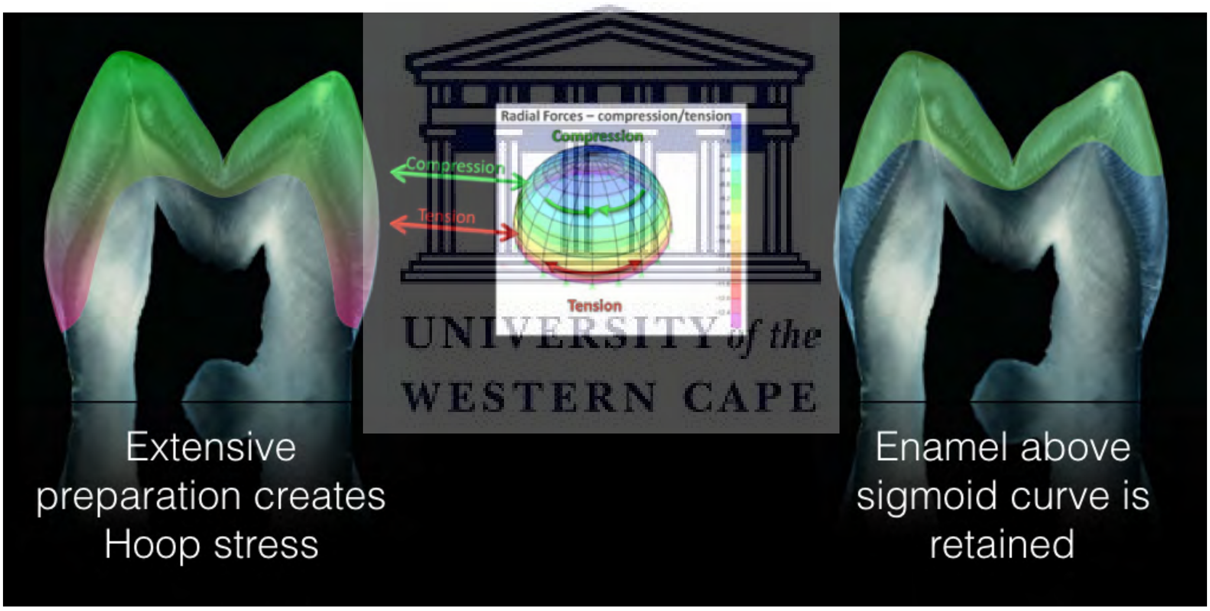
Figure 8: A graphical representation of the inflection point of dentine. (Wang and Weiner, 1998)



Enamel compression dome is in radial compression above inflection plane

Enamel compression dome is in radial tension below the inflection plane

Figure 9: A graphical representation of the transition of forces from radial compression to radial tension in the compression dome of a tooth (Wang and Weiner, 1998)**.**



Extensive preparation creates Hoop stress

Enamel above sigmoid curve is retained

Figure 10: Effect of extensive preparation design on stress distribution in the restorative material during compression of a restored molar tooth (Wang and Weiner, 1998)**.**

Ideal thickness of the occlusal veneer

By using the compression dome principal, and the advantages of adhesive, the occlusal veneer design can limit the axial wall extension while achieving high fracture resistance using relatively thin ceramics (Clausen, Abou Tara and Kern, 2010). Unfortunately, reports on the preparation guidelines for such indirect ceramic posterior occlusal veneers remain very limited (Guess *et al.*, 2013). Current guidelines for the minimal occlusal reduction, as recommended by most manufacturers, range from 1.5 mm to 2.0 mm (figure 2). These thickness requirements are mostly based on the results of laboratory tests that use full crown preparations and have limited clinical evidence when used in the occlusal veneer design (Ahlers *et al.*, 2009a). To complicate matters further, lower strength ceramic materials such as feldspathic or leucite-reinforced glass ceramics have been used in most of the studies to date (Guess *et al.*, 2013).

When one considers that higher strength ceramic systems, such as lithium disilicate glass ceramics have shown a significant increase in fracture resistance, it would be advisable to investigate the role that such materials can have on the occlusal veneer design.

The role of lithium disilicate in occlusal veneer design

When investigating the minimum thickness of monolithic lithium disilicate ceramic partial crowns or occlusal veneers, short-term and medium-term clinical data is promising, but long term data are still sparse (Pieger, Salman and Bidra, 2014). Current preparation guidelines still follow traditional glass ceramic protocol with thicker porcelains being advocated for additional strength figures 11 and 12).

In a study on bonded occlusal veneers made of e-Max CAD, Magne *et al* (2010) showed that restorations with a thickness of 1.2–1.8 mm withstood forces of up to 1000 N and thicknesses of 0.6–1.0 mm withstood 800 N . Guess *et al* (2013) studies on premolars showed that reducing the occlusal porcelain thickness from 1.5mm to 0.5mm did not significantly impair on the fracture resistance of the occlusal veneer restorations. As can be anticipated, complete veneer preparation of similar thickness along the axial walls did however result in lower failure loads due to the creation of tensile stresses (Guess et al., 2013).

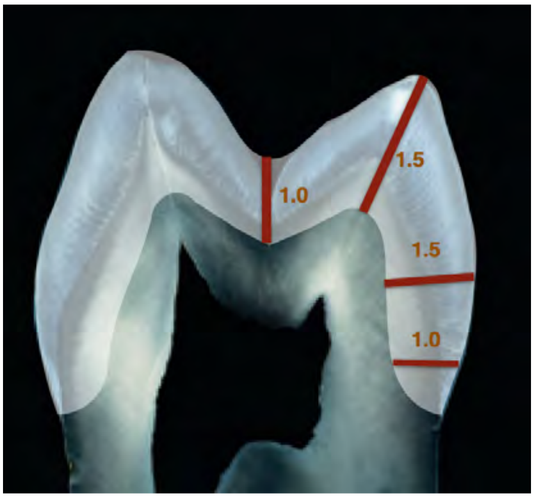


Figure 11: Current preparation guidelines for IPS e.max CAD crowns as recommended by the manufacturer. Minimum material thickness is given in mm (Ivoclar-Vivadent-AG, 2013).

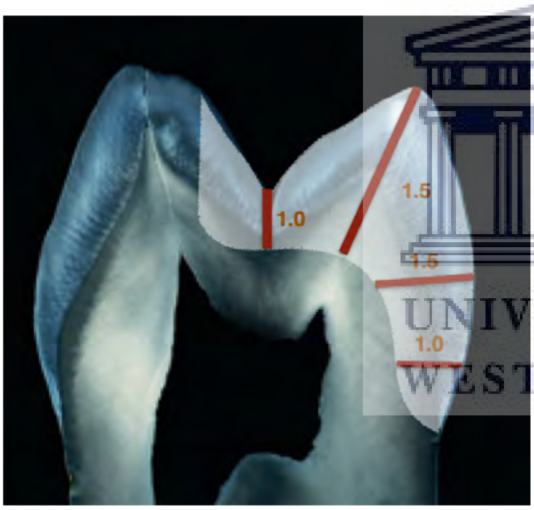


Figure 12: Current preparation guidelines for IPS e.max CAD partial crowns as recommended by the manufacturer (Ivoclar-Vivadent-AG, 2013).
Minimum thickness is given in mm.

In a recent study by Sasse *et al.*, the fracture resistance of varying thicknesses monolithic lithium disilicate restorations bonded to varying substrates were evaluated (Sasse et al., 2015). The results of the study revealed that all lithium dsilicate restorations of 0.7mm to 1.0mm thickness, bonded to varying substrates, survived occlusal load. Thinner restorations showed significantly less fracture resistance. Sasse’s findings (2015) are however in contrast with that of Guess (2013) who showed success at thicknesses as low as 0,5mm. The difference in the results could be explained by the difference in the adhesive protocol with Guess using adhesive cementation in a total etch technique and Sasse using self-etch protocol with no etching of the enamel. These conflicting finding leaves the clinician with no definitive information on the minimum ceramic thickness of posterior ceramic onlays and complete veneer restorations and the impact it has on its fracture behaviour.

1.5.4 Biomimetic dentistry

In an attempt to find the ideal thickness of restorative porcelain and the management of the underlying tooth structure, recent research has been focusing on understanding the composition of the natural tooth and finding ways to mimic it (Bazos and Magne, 2011). This has seen the development of bio-emulation as a new aspect of dentistry, corresponding to the reproduction of the natural model via spatial, structural and optical histo-anatomic emulation (Sarikaya, 1994).

Biomimetics or bio-emulation associates two fundamental attributes at the core of modern care: tissue preservation and adhesion (Tirlet *et al.*, 2014). By understanding the components of the natural tooth (see figure 5), Biomimetics or Bio-emulation aims to use these attributes to reproduce and biomimetically match the restorative materials and natural tooth substrates (Bazos and Magne, 2011).

Because of sophisticated adhesive techniques and the progress that has been made in material technology and adhesives, it is possible to produce a biomimetic match between aesthetic substitution materials and the anatomical substrates of the natural tooth (Bazos and Magne, 2011). Following this biomimetic concept, dentine is replaced with a dentine-like material (resin composite) and enamel with an enamel-like material (porcelain). This has led to the combination of different restorative materials in techniques that are not only aimed at producing strong restorations, but also increase the longevity of the underlying tooth (Guess *et al.*, 2013). It allows for the conservation of the biological, esthetic, biomechanical and functional properties of enamel and dentine (Tirlet et al., 2014).

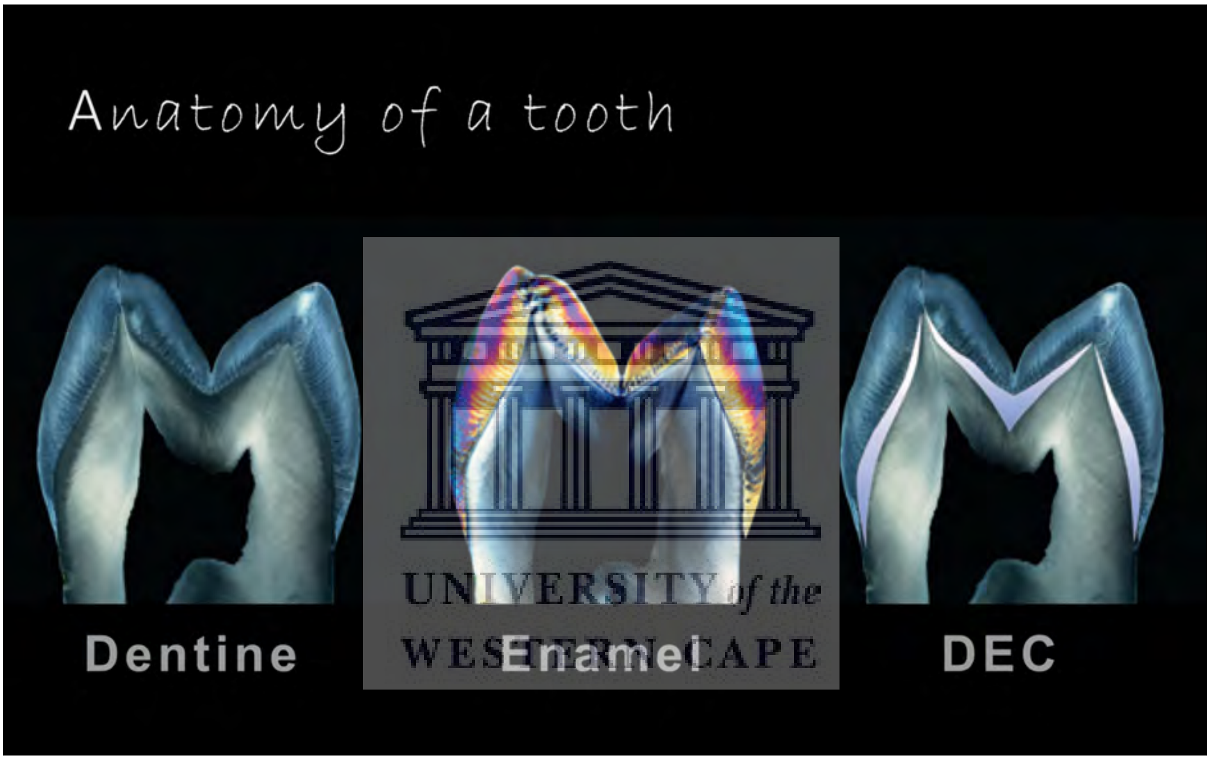


Figure 13: A graphical representation of the three major components of a neutral tooth. Dentine, enamel and the dentine-enamel-complex (DEC).

Achieving this goal is reliant on the properties and effective management of the restorative material. The clinician needs to understand the ideal balances between the restorative thickness and resultant strength. Achieving the ideal thickness of the restorative material that provides clinically relevant strength, while at the same time retaining the maximum amount of sound tooth structure so as to increase the longevity of the tooth.

Current literature has investigated the ideal thickness of the restorative lithium disilicate as it is bonded to a partial resin substrate in the bio-substitutive model (Sasse *et al*., 2015). However, the author has not identified any research that has directly compared the use of such a bio-substitutive approach with a more traditional approach in cavity design where no resin dentine-replacement is used. Thus, the purpose of this study was to evaluate the ideal thickness of lithium disilicate ceramic restorations that are bonded to a resin dentine-replacement and evaluating this thickness against a preparation design that does not make use of the bio-substitutive model.

Furthermore, such a restorative choice could have a far-reaching impact on the strength and longevity of the underlying tooth structure, contributing to, or preventing catastrophic damage. To understand the impact of the preparation design and the use of a bio-substitutive model could have on the underlying tooth structure, the forces that play a role in the oral environment should be understood.

1.6 The Maximum bite forces in humans

When considering the performance of restorative materials and the impact that changes in preparation design could have on its success, one should take into consideration:

- the maximum fracture value of the tooth
- the maximum bite force in the human oral environment

In current literature the mean fracture value of untreated molar teeth varies greatly, with the methods for standardising the maximum fracture resistance proving to be very difficult. In a recent study, Yasa *et al*. (2015) showed a mean fracture strength of untreated molar teeth to be 2,462N with a standard deviation of ±568.98N, a minimum of 1,294N and a maximum of 3,688N. With such variations, it is very difficult to predict how a tooth would react under load. Even when one considers this unpredictability, structural damage or loss of tooth structure causes a drastic reduction in these values (Teixeira *et al*., 2016).

In addition to the maximum fracture resistance of healthy teeth, the maximum bite force generated by the human oral environment should also be considered. The results of numerous laboratory experiments that investigated the bite forces generated in the oral environment vary considerably. This is due to several factors including: subject gender and age, food type, jaw disorders, tooth quality, and muscular strength, Osborn (1996) reports five criteria that increase the maximum bite force independent of the subject being tested. The factors that increase force are (i) tilting the bite force forward, (ii) keeping the jaw perpendicular to the occlusal plane as it is opened, (iii) placing teeth nearer the midline, (iv) raising teeth height for forward bite forces, and (v) tilting the articular surface of the condyle forward (Osborn, 1996). Bite force is also dependent on the teeth that are in direct contact with the food. Incisors are located in the front of the jaw and have the least mechanical advantage. Conversely, molars at the rear, have the greatest potential for mechanical advantage and have evolved to compress food between occlusal surfaces and shear food during grinding motions. This increase in occlusal load of posterior teeth plays an important role in the choice and design of the posterior restorative material.

Force measurement has been conducted to assess both the force required for mastication and maximum bite force. Common foods such as carrots, biscuits, and cooked meats produce forces in the range of 70-150 N on a single tooth (Anderson, 1956). Forces on all contacting teeth during mastication range between 190 and 260 N (Gibbs *et al*., 1981). Maximum bite force is variable between experiments, but generally falls within the range of 500-800 N. This maximum bite force as reported by several different articles for young, healthy subjects is shown in Table 18. It is believed that the sensation of pain limits the maximum bite force of individuals by blocking inhibitory pathways between the periodontium and elevator motoneurons (Orchardson & MacFarlane, 1980). This has been studied in experiments where a local anaesthetic is applied to the biting teeth, resulting in increased maximum bite force (Waltimo & Könönen, 1995).

These maximum masticatory forces present during function and maximum load contribute greatly to the fatiguing of both the restoration and remaining tooth structure. When evaluating the performance of minimally invasive lithium disilicate restorations, these maximum masticatory forces together with the maximum load of healthy teeth, should be considered. Such values can give a better indication of the potential long-term clinical performance of the restoration and remaining tooth.

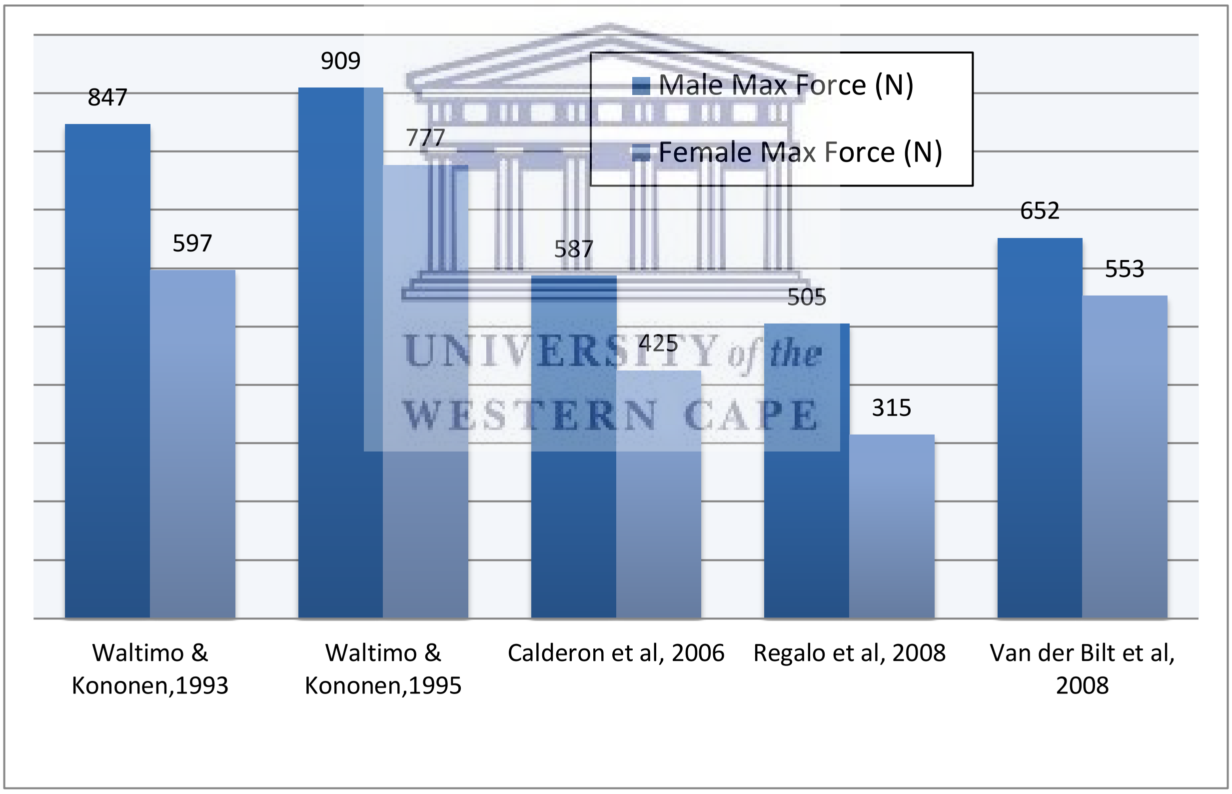


Figure 14 Maximum bite force in male and female subjects as reported by different articles. Re3f

CHAPTER 2

Purpose of study

In an attempt to create the ideal biologically sound restoration, clinicians have adopted the use of revised cavity designs and conservative porcelain restorations in a bio-substitutive model. Combinations of direct and indirect restorative techniques are used in an attempt to alleviate most complications encountered during the restoration of posterior teeth.

When evaluating these developments, a number of questions arise:

- Does the use of composite as dentine replacement increase the fracture resistance of occlusal veneer porcelain restorations?
- What is the ideal thickness of the occlusal veneer porcelain restorations?
- How do these aspects affect the restorability, and ultimately the long-term survival of the underlying tooth?

1.7 Aim

The aim of this in-vitro study was to evaluate the influence of variations in ceramic thickness and types of cavity design on the fracture resistance of different thicknesses of lithium disilicate ceramic restorations.

1.8 Objective

1. To determine the fracture resistance of CAD / CAM monolithic lithium disilicate restorations of 1mm over the cusp with fissure thickness of 0.7mm when bonded to different substrates namely: dentine, enamel and composite restorative material.
2. To determine the fracture resistance of CAD / CAM monolithic lithium disilicate restorations of 0.8mm over the cusp with fissure thickness of 0.5mm when bonded to different substrates namely: dentine, enamel and composite restorative material.
3. To determine the impact of cavity design optimisation and bio-substitution, using composite build up to replace missing dentine, on the fracture resistance of CAD / CAM monolithic lithium disilicate restorations of thickness 1mm (0.7mm in fissure) and 0.8mm (0.5mm in fissure).
4. To evaluate the fracture patterns of the restoration and underlying tooth structure when using the various thicknesses of CAD / CAM monolithic lithium disilicate restorations bonded to dentine, enamel and composite restorative material using different cavity designs.

CHAPTER 3

Materials and methods

1.9 Materials

This is an *in vitro* comparative study conducted at the Oral and Dental Research Laboratory of the Tygerberg Hospital. The following restorative materials were used in this study:

1.9.1 Restorative porcelain:

IPS e.max CAD

IPS e.max CAD is a high-strength lithium-disilicate-based glass ceramic. With strength of 360 MPa, the material is suited to the fabrication of fully anatomical and partially reduced anterior and posterior crowns (Ivoclar-Vivadent, 2013). The blocks are cast in one piece. A continuous production process based on glass technology (pressure-casting procedure) is utilized in the manufacture of the blocks. This new technology, which largely differs from the sintering process employed in the production of Empress / Empress 2 ingots, uses optimized processing parameters, which prevent the formation of defects (pores, accumulation of pigments.) in the body of the block. Partial crystallization ensures that the blocks can be easily processed in an intermediate crystalline phase, enabling rapid machining with CAD / CAM systems (blue state). The partial crystallization process leads to the formation of lithium-metasilicate crystals, Li_2SiO_3, which are responsible for the material's favourable processing properties, comparatively high strength and high-edge stability (Ivoclar-Vivadent-AG, 2013). Following the milling procedure, the restorations are tempered and reach the final state. In the course of this process, lithium disilicate crystals, $Li_2Si_2O_5$, are formed, which produces a ceramic with the final shade and desired high strength. Table 4 shows the physical properties of IPS e.max.

Partially crystalized IPS e.max CAD

The microstructure consists of 40% lithium metasilicate crystals (Li_2SiO_3) embedded in a glassy phase. The grain size of the platelet-shaped crystals is in the range of 0.2 to 1.0 µm. The etched-out areas in Figure 15 show the lithium metasilicate crystals.

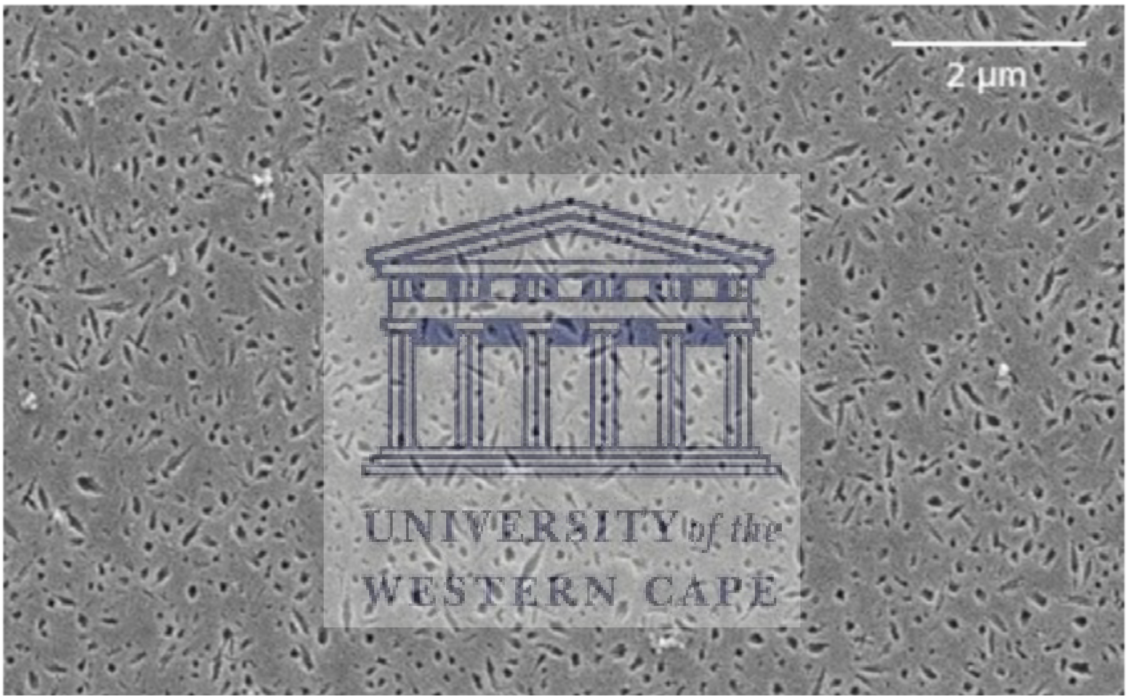


Figure 15: SEM of IPS e.max CAD Lithium-Metasilicate (blue phase) (with permission from Ivoclar Vivadent).

Fully crystalized IPS e.max CAD

After tempering at 850°C, the microstructure changes to consist of approximately 70% fine-grain lithium disilicate crystals, $Li_2Si_2O_5$, which are embedded in a glassy matrix. By etching with hydrofluoric acid vapour, the glassy phase is dissolved and the lithium disilicate crystals become visible (Figure 15). The physical properties of IPS.max CAD are shown in Table 4.

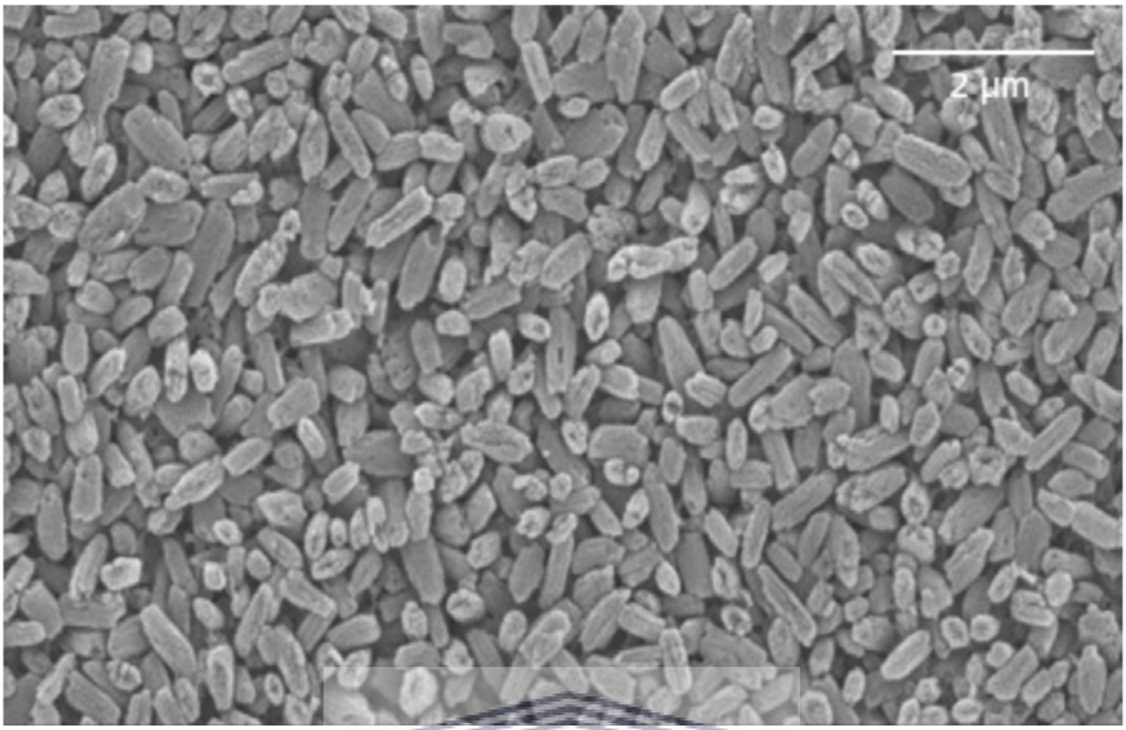


Figure 16: SEM of IPS e-max CAD Lithium-Disilicate (with permission from Ivoclar Vivadent technical specifications).

Table 3: Physical properties of IPS e.max CAD as documented by the manufacturer. (Ivoclar Vivadent, Schaan, 2005/06)

Physical properties	Partially crystallized state	Fully crystallized state
Physical properties Biaxial strength (ISO 6872)	130 ± 30 MPa	360 ± 60 MPa
Fracture toughness (SEVNB)	0.9 – 1.25 MPa m½	2.0 – 2.5 MPa m½
Vickers hardness	5400 ± 200 MPa	5800 ± 200 MPa

1.9.2 Cementation material

Variolink Esthetic DC

Variolink Esthetic (Ivoclar Vivadent, Schaan Lichtenstein) is a colour-stable, adhesive luting system for the permanent cementation of glass-ceramic, lithium disilicate glass-ceramic, composite and oxide ceramic restorations (inlays, onlays and veneers). Variolink Esthetic is offered in two versions; Variolink Esthetic LC, which is purely light-curing, and Variolink Esthetic DC which is dual-curing. Table 5 summarizes the indications for use of Variolink Esthetic DC and LC according to the manufacturer's guidelines. Variolink Esthetic DC can be used with opaque restorations, whereas the LC variant should only be used for thin restorations with a thickness less than 2mm, and sufficient translucency (e.g. restorations made of IPS e.max Press and CAD HT). For this study, a DC cement was used.

Table 4: Indications for use of Variolink Esthetic LC and DC. (Braziulis, 2014)

✓" indicates where the cements can be used. "?" Indicates where reduced thickness inlays, onlays and crowns can be used in combination with LC cements if the material thickness allows for sufficient light penetration for complete polymerisation.

	Vaiolink Esthetic LC	Variolink Esthetic DC
Inlays	?	✓
Onlays	?	✓
Partial crowns	?	✓
Occlusal veneers	✓	✓
veneers	✓	✓
crowns	✗	✓
bridges	✗	✓

Composition of Variolink Esthetic

The monomer matrix of Variolink Esthetic is composed of urethane dimethacrylate and other methacrylate monomers. The inorganic fillers are ytterbium trifluoride and spheroid mixed oxide. Initiators, stabilizers and pigments are additional ingredients.

Adhese Universal

Adhese Universal (Ivoclar Vivadent, Schaan Lichtenstein) is a newly marketed universal adhesive system indicated for the bonding of porcelain and composites. This single-component, light-cured adhesive is used for both direct and indirect bonding procedures. Adhese Universal is based on the Adhese product family and Multilink Primer. It contains methacrylate, ethanol, water, highly dispersed silicon dioxide, initiators and stabilizers.

Adhese Universal is indicated for bonding or repairing light-cured composite and compomer restorations, for core build ups with light-, self- and dual-curing composites, for the adhesive cementation of indirect restorations with light- or dual-curing luting composites, for sealing prepared tooth surfaces before the temporary / permanent cementation of indirect restorations (e.g. immediate dentine sealing / dual-bonding technique) and for desensitizing hypersensitive cervical areas. As Adhese Universal is always light-cured, it is contraindicated in situations where sufficient illumination cannot be ensured, e.g. the cementation of root canal posts.

Adhese Universal is indicated for use with the total-etch, self-etch techniques and with dual-cure materials without a separate activator. It is not, however, indicated as a separate primer for restorative substrates according to the manufacturer.

Due to the adhesive acidic monomers inhibition of the polymerization of auto-cured and dual-cure composite luting cements, Adhese Universal requires polymerisation before seating of indirect restorations. The subsequent layer thickness can be an issue when seating indirect restorations. Adhese Universal is always “thinned out” with dispersed air (which is aided by the inclusion of thixotropic silica) and subsequently light-cured before seating indirect restorations – eliminating the need for an additional dual-cure activator. Curing Adhese Universal immobilizes the acid monomers and allows good polymerization at the adhesive-cement interface without a separate activator. The cured adhesive exhibits a layer thickness of < 10µm on bovine dentine, enabling the seating of even very tight-fitting indirect restorations and, when combined with Variolink II luting composite, there is an increase in inlay elevation of < 50 µm, which will not negatively affecting accuracy of fit (Ivoclar-Vivadent-AG, 2013).

In addition, the shear bond strength of Adhese Universal to aged composites was evaluated in in-house studies conducted by Ivoclar-Vivadent (Ivoclar-Vivadent-AG, 2013). All the composites achieved shear bond strength values of around 25-26 MPa. The bond strength exceeded the cohesive strength of the material with 100% of the samples undergoing cohesive failure in the test.

Table 5: A summary of the indications for universal bonding agents on the market (adapted from Ivoclar-Vivadent-AG, 2013). ✓ indicates where the cements can be used

Product	Total-etch	Self-etch	Dual cure	Bonding to LiDi	Bonding to Zirconia
All-bond unversal	✓	✓	✓	✓	✓
Peak universal	✓	✓	×	×	×
Adhese Universal	✓	✓	✓	✓	✓
Optibond	×	✓	✓	✓	✓

Monobond etch and prime

Monobond etch-and-prime (ME&P - Ivoclar Vivadent, Schaan, Lichtenstein) is a novel single bottle ceramic primer, which allows for etching and silanisation of the glass ceramic surface in one step. It contains a trimethoxypropyl methacrylate for silanisation and a new polyfluoride for the etching step. The etching creates a roughness pattern, which is less pronounced than with hydrofluoric (HF) gel, but as efficient for bonding (Wille, Lehmann and Kern, 2017).

Ammonium polyfluoride reacts with the silicon on the glass ceramic without the release of HF, due to the high chemical affinity between silicon and fluoride (Roman-Rodriguez *et al.*, 2017). After the extra-oral application, the remaining liquid is thoroughly rinsed off. Once dry, a thin silane layer in molecular scale remains at the luting surface, which reacts via the methacrylate group with the luting composite during curing (Roman-Rodriguez *et al.*, 2017).

During in-house studies, the manufacturer evaluated the bond strength of Monobond etch-and-prime on various ceramic substrates (Völkel and Braziulis, 2015). Monobond etch-and-prime produced a high aging-resistant adhesive bond on various ceramic material, similar to that produced by the silane agent Monobond Plus after hydrofluoric acid etching (Völkel & Braziulis, 2015).

1.10 Methods

Forty routinely extracted human molar teeth were used in this study, after each patient received an information sheet and patient consent was obtained (Appendix 1 and 2). All molar teeth without any caries or fillings were cleaned and stored in a 0.1% thymol solution prior to use. The roots of the teeth were then embedded in custom made standard UPVC (unplasticized polyvinyl chloride) cylinders (Ø 15 mm) and positioned along their long axis with auto-polymerizing acrylic resin material (Technovit 4000, HeraeusKulzer, Wehrheim, Germany). They were positioned so that the cement-enamel junction was located 2 mm above the level of the embedded resin.

Specimens were divided randomly into two groups (*n* = 20 each) (figure 17.

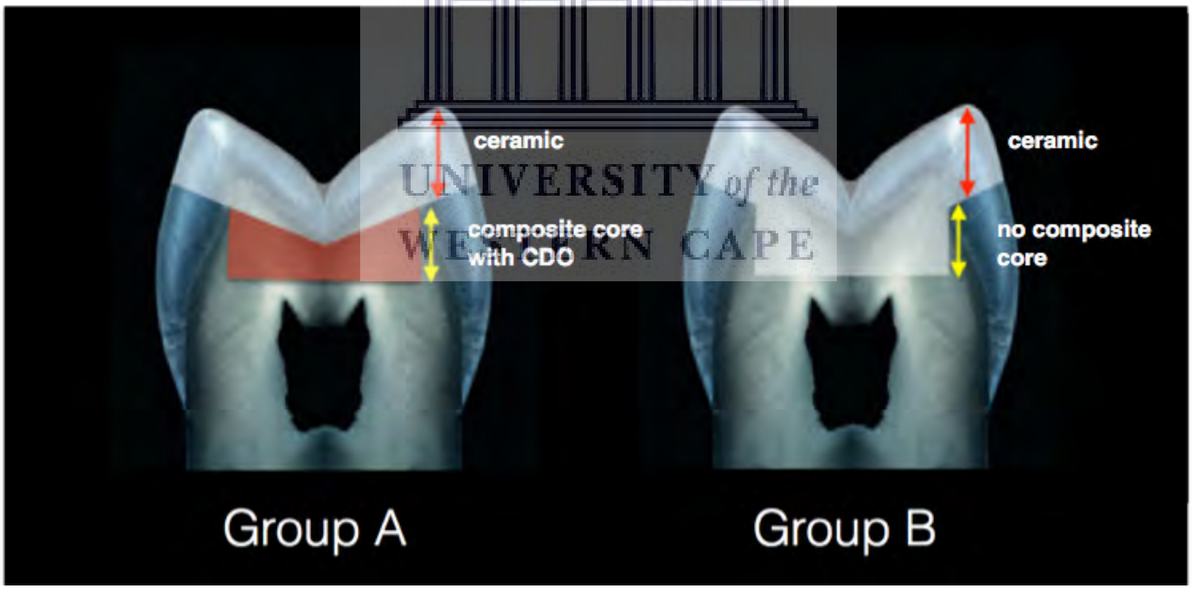


Figure 17: Preparation design of Groups A & B .

Group A has been prepared with a class I cavity that is filled with composite.

In Group B the class I cavity is left unfilled and was replaced by monolithic ceramic only.

Group A: Coronal crown preparation (butt joint) was prepared, using a pre-shaped diamond wheel under constant water cooling, until all central dentine was exposed and a circumferential enamel margin of at least 1mm was present (Figures 18a and 18b). An additional Class I cavity that included all the exposed dentine was prepared to a depth of 1mm from the central fissure using a round size 10 bur (Figures 18c and 18d). This was done to simulate the clinical situation where most teeth may present with Class I cavities. The prepared class one cavity was then restored with composite material (Tetric N-Ceram, Ivoclar Vivadent, Schaan, Liechtenstein) using a single bottle bonding system (Tetric N-Bond Universal, Ivoclar Vivadent, Schaan) (Figure 17e). A 130-degree preparation angle was maintained in the buccolingual and checked with a pre-shaped guide (Image 18f). The preparation was then smoothed and all sharp edges rounded.

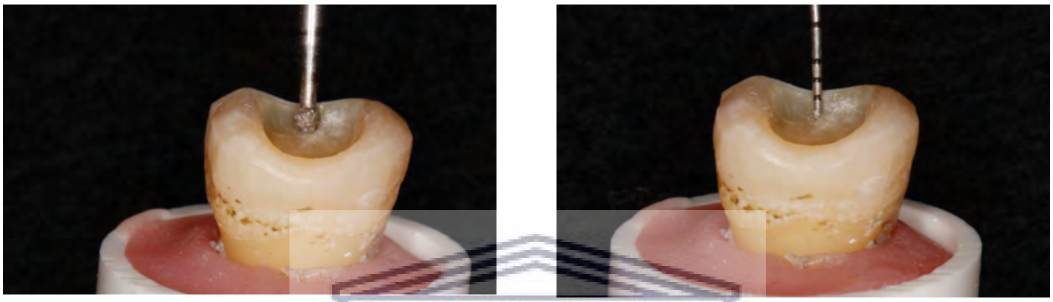
Group B: Coronal crown preparation and Class I one cavity preparation as above. The Class I cavity was left unfilled (Figures 18g and 18h). A 130-degree preparation angle was maintained in the buccolingual using a pre-shaped gauge to 130 degrees. Preparations were smoothed and sharp edges rounded.

In both groups, the circumferential outline of the preparation was strictly within the enamel. An angle of 130^o was maintained between the cusps.

Group A

a) Unprepared tooth

b) confirmation of 130^{o} inter-cuspal angle using a pre-shaped guide



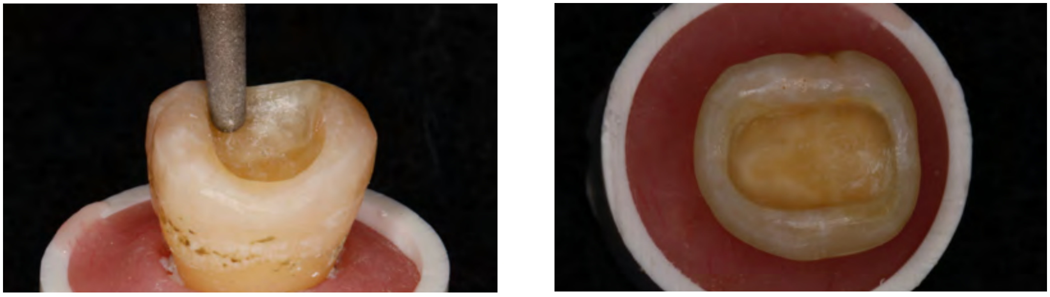
c) class I cavity created using a no 10 round bur

d) confirm of depth of cavity at 1mm using periodontal probe

e) complete filling of Class 1 cavity using composite restorations

f) Final preparation checked using pre-shaped gauge

Group B



g) unfilled class I cavity smoothened for restoration

h) Final preparation

Figure 18 Laboratory process followed to create Group A and B preparations

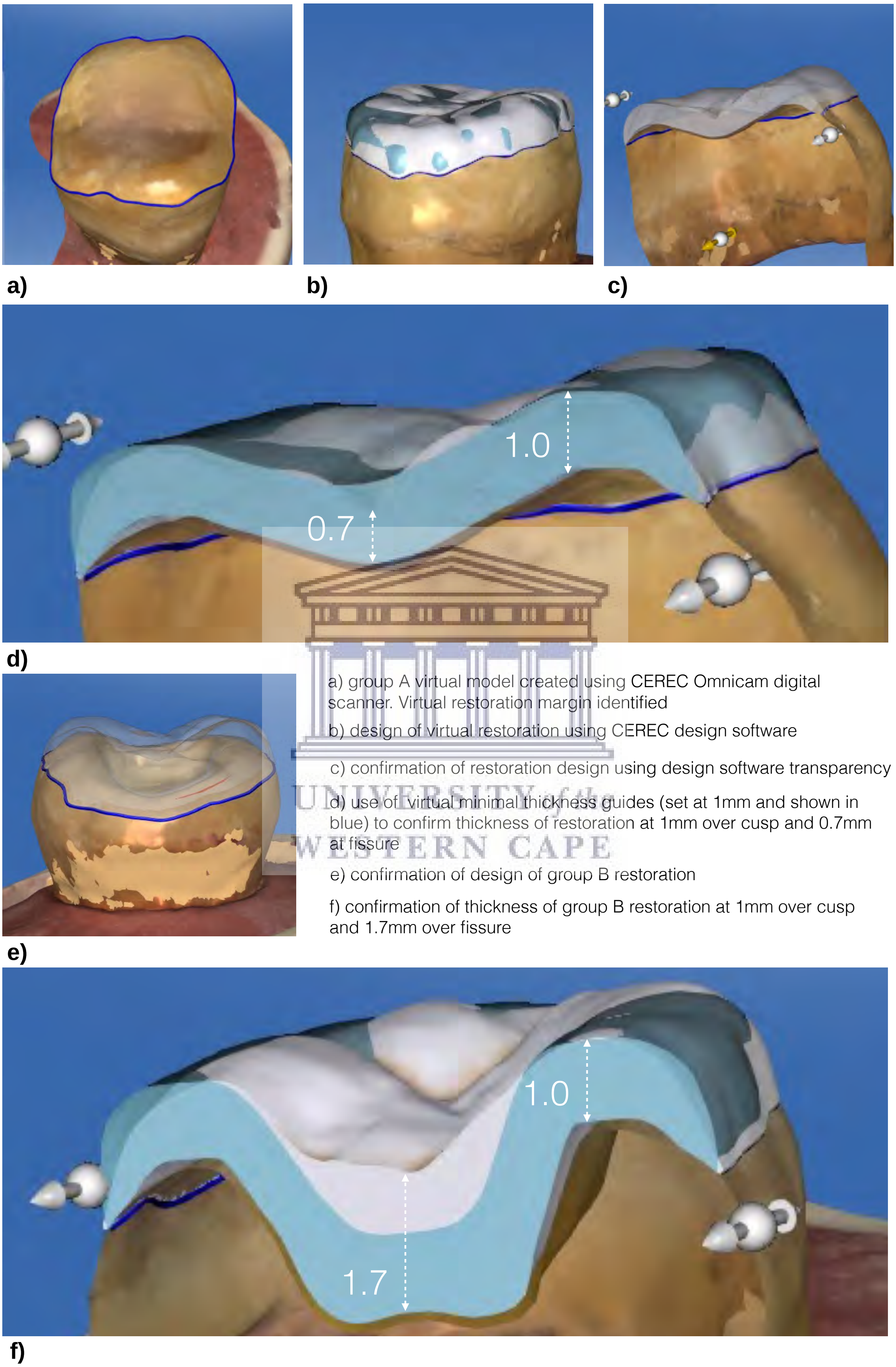
The process of designing and adhesive placement of the CAD/CAM lithium disilicate restorations was then followed. A preliminary optical impression (CEREC Omnicam; Sirona Dental Systems GmbH, Bensheim, Germany) was made and the restoration designed (Figures 19a to f). The design and manufacturing of standardized occlusal veneers were done using the CEREC database and generated with the CEREC version 4.4 software (Sirona Dental Systems GmbH).

Table 6: Distribution of groups and their thicknesses

	Substrate	**Ceramic thickness**
Group A	Enamel and composite filled dentine cavity preparation	1mm at cusp with 0.7mm fissure depth
		0.8mm at cusp with 0.5mm fissure depth
Group B	Enamel and unfilled dentine cavity preparation	1mm at cusp with 1.7mm fissure depth
		0.8mm at cusp with 1.5mm fissure depth

Each group (Groups A and B) were further divided into two groups based on the restorative ceramic thickness as shown in Table 9 For Group A1, there was a reduction of 1mm over the cusp and 0.7 in the fissure and for Group A2, there was a reduction of 0.8mm over the cusp and 0.5mm in the fissure. For Group B1, the reductions were 1mm over the cusp and 1.7mm in the fissure and for Group B2, the reductions were 0.8mmm over the cusp and 1.5mm over the fissure (Table 9). The additional 1mm of ceramic thickness over the fissure of Group B allowed for the restoration of the void created by the 1mm deep class 1 cavity that was left unfilled.

To standardise the study and in order to achieve a constant ceramic thickness, the occlusal surface received a semi-anatomic shaping. In the CAD/CAM software, the occlusal surface of the tooth was virtually elevated and then reduced again until the desired fissure thickness was obtained. Software design tools were used to create the defined cuspal height (Figures 19d and 19f).



a) group A virtual model created using CEREC Omnicam digital scanner. Virtual restoration margin identified

b) design of virtual restoration using CEREC design software

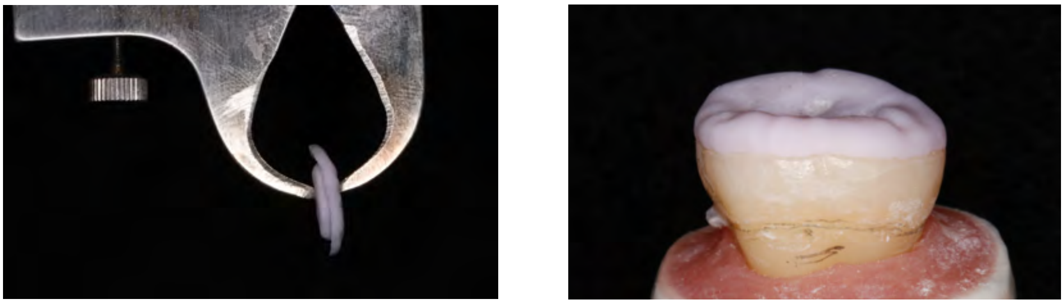
c) confirmation of restoration design using design software transparency

d) use of virtual minimal thickness guides (set at 1mm and shown in blue) to confirm thickness of restoration at 1mm over cusp and 0.7mm at fissure

e) confirmation of design of group B restoration

f) confirmation of thickness of group B restoration at 1mm over cusp and 1.7mm over fissure

Figure 19: CAD/CAM design of restorations of Groups A and B.



a) confirmation of thickness of ceramic using manual callipers

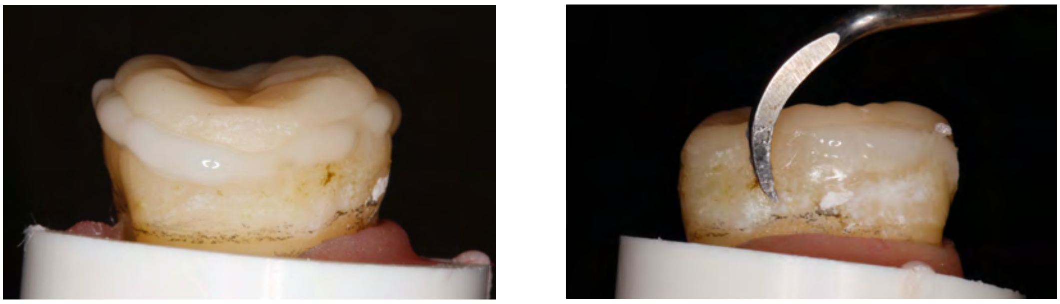
b) visual confirmation of fit of ceramic before crystallisation

c) inspection of intaglio after crystallisation

d) Application of etch and prime to condition intaglio surface

e) selective etch of enamel for 20 seconds

f) application of adhesive on tooth surface



g) cementation of ceramic

h) removal of excess cement after curing

Figure 20: Manufacture, conditioning and cementation of restorations.

The uncrystallised ceramic occlusal veneers were then milled out of lithium disilicate blocks (IPS e.max.CAD, Ivoclar Vivadent, Schaan, Liechtenstein) using the CEREC MCX Wet/Dry Milling Unit (Sirona Dental Systems GmbH). All restorations were milled in Fine Mode with the sprue at the lingual surface. Restorations were visually inspected for possible milling cracks and minimal thickness and fit was confirmed (Figures 20 and 20b). All restorations were then crystallized according to the manufacturer's specifications using a Programat CS2 (Ivoclar Vivadent) set for standard crystallization on setting no 1. After crystallisation and cooling, the restorations were polished using Eva Diapol and Eva Diacera polishing wheels.

During cementation, all enamel surfaces were pre-treated with 37% phosphoric acid for 20 seconds (Figure 20e). The preparation was then actively rinsed with water for 60 seconds and dried. A self-etching primer (Tetric N-Bond Universal, Ivoclar Vivadent, Liechtenstein) was applied onto the bonding surface of the tooth with an innovative application tip, Viva Pen (Ivoclar Vivadent, Lichtenstein) for 20 seconds (Figure 20f) and the surface gently air-dried. The bonding surface was then light-cured using a dental curing light (Bluephase Style, Ivoclar Vivadent, Schaan) for 10 seconds. Light output was checked prior to use with a CureRite device (Dentsply, USA) and was recorded at 1200mW/cm^2. This was checked after every five uses.

The bonding surfaces of the ceramic restorations were actively agitated for 20 seconds (with an additional waiting period of 40 seconds) using the self-etching glass ceramic primer (Monobond Etch-and-Prime Ceramic Primer, Ivoclar Vivadent, Lichtenstein). All restorations were thoroughly cleaned using water spray for 60 seconds and then air-dried (Figure 20d).

A dual cure luting composite (Variolink Esthetic, Ivoclar Vivadent) was dispensed from the automix syringe onto the intaglio surface of the restoration and onto the fissure area of the tooth. The restoration was positioned by hand and kept in place. After spot curing using a dental curing light (Bluephase Style, Ivoclar Vivadent) for two seconds per surface, all excess resin cement was removed (Figures 20g and 20h). All margins were covered with a glycerine air block (Liquid Strip, Ivoclar Vivadent) and light-cured for 20 seconds from all aspects (total of 180 seconds). After cleaning of excess cement from the margins (figure 20h), all margins were polishing using Eve Ecoceram polishing burs and specimens were stored in water for 24 hours at 37°C in order to achieve complete curing.

After water storage, all specimens were thermo cycled 7500 times between 5°C and 55°C in water with a 30 second dwell time at each temperature. The specimens were then loaded in a universal testing machine (Zwick Z010/TN2A, Ulm, Germany). A steel bar with a 6mm ball end was centred on the main fissure of each specimen in order to apply the load evenly to the triangular ridges of the oral and buccal cusps. Additionally, a 0.6mm tin foil was placed between the ball end and the specimen in order to distribute the load homogenously. The stainless-steel bar descended at a crosshead speed of 1 mm/min while computer software (TestXpert II, Zwick, Ulm, Germany) recorded the load in Newton (N).

The specimens were loaded to intervals of 500N, 800N, 1000N, 1200N, 1500N, 1700N and 2000N. After each loading interval, the specimens were inspected for any sign of crack formation and photographed under standardized conditions at x1.5 magnification (Canon EOS 70D with Canon EF 100mm f/2.8L Macro IS USM Lens). Once crack formation was noted, the specimens were loaded to failure and the maximum load recorded. Two examiners were used to assess for any crack formation.

1.11 Data Analysis

Data was captured and exported into Statistical Package for the Social Science (SPSS) version 21 (IBM, USA) for statistical analysis. Kruskal Wallis analyses with group and thickness as independent variables were evaluated. The mean fracture values expressed in Newtons (N) were compared for statistical differences between the groups and a p value < 0.05 was considered as significantly different.

CHAPTER 4

Results

1.12 Fracture strength testing

When evaluating the maximum fracture values of the two preparation designs (group A and B) at two different restorative thicknesses (1mm with a fissure of 0.7mm, and 0.8mm with a fissure of 0.5mm), the following observations were noted:

Table 7: Dispersion in the observation of fractures

Group	Thickness	N	Mean	Standard Error of Mean	Minimum	Maximum	Range
A	1 mm	10	2460.70	100.02	2026.00	2965.00	939.00
	0.8 mm	10	1523.80	217.72	380.00	2340.00	1960.00
	Total	20	1992.25	158.57	380.00	2965.00	2585.00
B	1 mm	10	3142.60	328.35	1835.00	4560.00	2725.00
	0.8 mm	10	2591.80	280.63	1445.00	3967.00	2522.00
	Total	20	2867.20	219.50	1445.00	4560.00	3115.00

In general, Group B (ceramic only) restorations showed higher fracture resistance at a mean value of 2867N compared to that of Group A (composite core) with a mean value of 1992N.

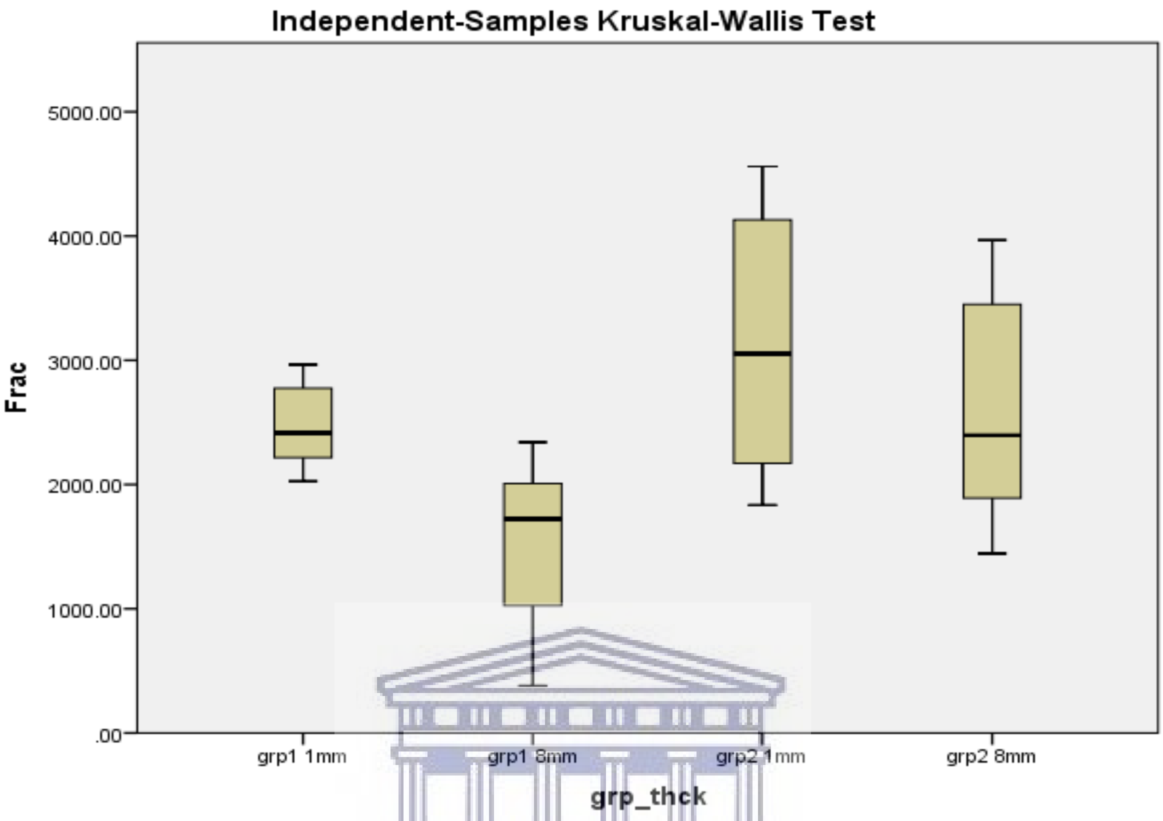


Figure 21: Results of Kruskal-Wallis analysis with group and thickness as independent variables shown in box plot. Fracture (Frac) and Group Thickness (Grp_thck)

The box plot of figure 21 shows the median, minimum and maximum fracture values as well as the upper and lower quartiles of the observed maximum fracture values.

Table 8: P**airwise comparison of groups and thicknesses.**

Pairwise Comparisons of Groups and Thicknesses					
Grp A - Grp B	Test Statistic	Std. Error	St Test Statistic	Sig.	Adj. Sig.
Grp A 8mm-grp A 1mm	14.60	5.23	2.793	.005	.031
Grp B 8mm-grp B 1mm	5.20	5.23	.995	.320	1.000
Grp A 1mm-grp B 1mm	-4.30	5.23	-.822	.411	1.000
Grp A 8mm-grp B 8mm	-13.70	5.23	-2.620	.009	.053

Each row tests the null hypothesis that the Sample A and Sample B distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is .05.

Intra-group variations in maximum fracture value

Group A (composite core preparation):

When evaluating the mean fracture values of Group A (composite core preparation) at the different porcelain thicknesses, there was a significant difference in the maximum fracture value between the 1.0mm and 0.8mm thick porcelain ($p < 0.05$, Kruskal-Wallis Test). The mean fracture value of 1.0mm porcelain thickness (2460 Newton) was significantly greater than that of 0.8mm porcelain thickness (1523 Newton).

Group B (no composite core):

When evaluating the fracture values of Group B (no composure core preparation) at the different porcelain thicknesses, there was no significant difference in the maximum fracture values of the two porcelain thicknesses ($p > 0.05$, Kruskal-Wallis Test). The mean fracture value at a thickness of 1.0mm porcelain thickness (3142 Newton) was not significantly different to that of 0.8mm porcelain thickness (2591 Newton).

Inter-group variations in maximum fracture value

Group A & B (1mm thickness):

When evaluating the fracture values of the 1mm thick porcelain restoration with two different preparation designs of Group A (class I cavity filled with composite core) and B (class I cavity with no composite core), no statistical significance was noted in the maximum fracture resistance ($p > 0.05$, Kruskal-Wallis test).

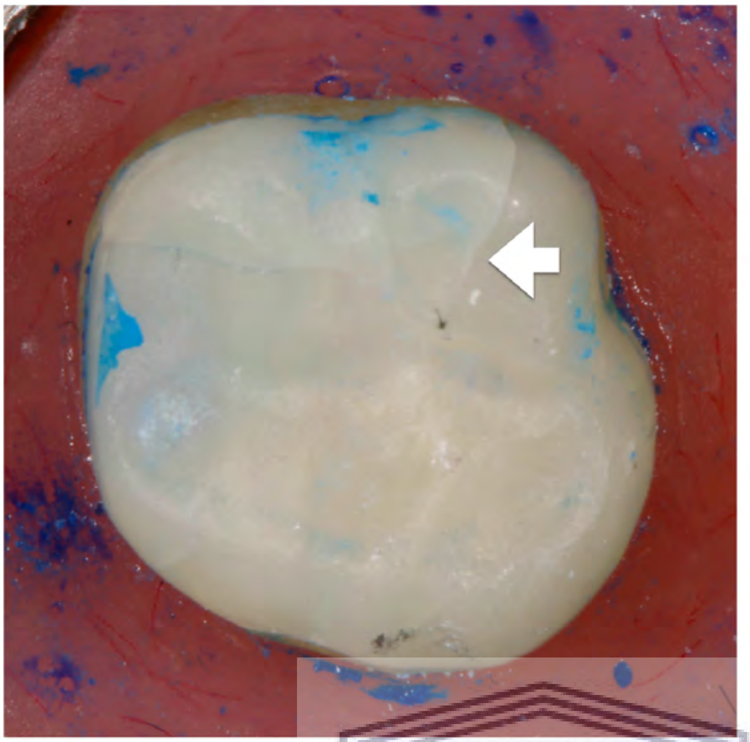
Group A & B (0.8mm thickness):

When evaluating the fracture values of the 0.8mm thick porcelain restoration with two different preparation designs of Group A (Class I cavity filled with composite core) and B

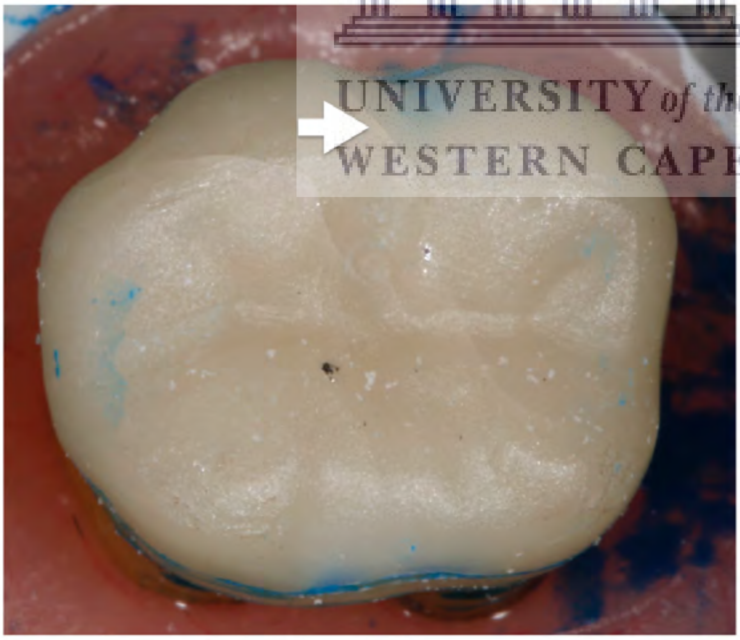
(Class I cavity with no composite core), a statistical significance was noted in the maximum fracture resistance ($p < 0.05$, Kruskal-Wallis test).

1.13 Load values at initial crack identification

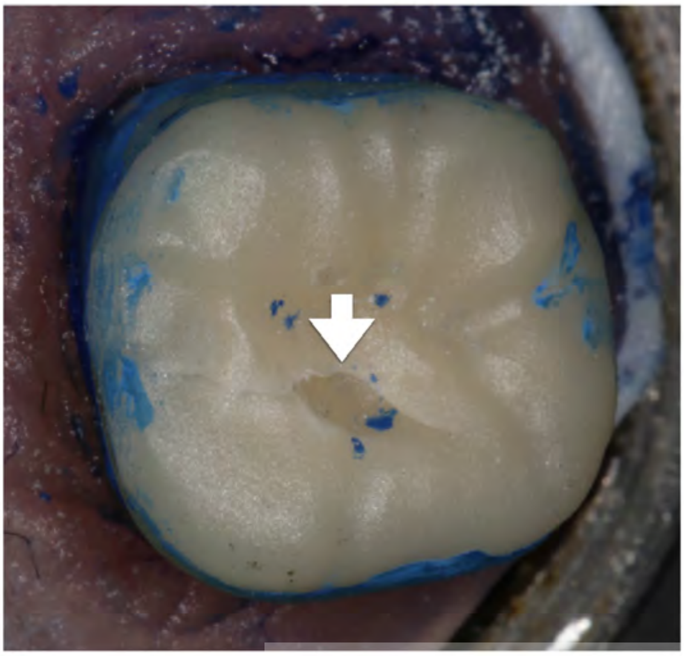
Each specimen was visually evaluated for the presence of any cracks at increasing load values of 500N, 800N, 1000N, 1200N, 1500N, 1700N and 2000N (Figure 22). With reported maximum masticatory forces ranging between 500N and 800N, the number of specimens with crack formation under 800N was calculated as a percentage of the total number of specimens (Total N = 10). The following observations were noted:



a) specimen from group A 0.8mm showing initial crack at 800N.



b) specimen from group A 1.0 mm showing initial crack at 1000N.



c) specimen from group B 0.8mm showing initial crack at 1500N.

d) specimen from group B 1 mm showing no sign of crack formation at 2000N

Figure 22: Each specimen was evaluated for signs of crack formation at intermittent loading values.

(a-d) show the cracks noted for each group and subgroup and the load value at which the crack was noted.

Group A: Class I cavity with composite core

In the porcelain thickness of 0.8mm 60% of the specimens showed signs of fracture of the porcelain when 800N force was applied. In the porcelain thickness 1mm, the number of cracked specimens decreased, with 20% of specimens showing signs of crack formation at values under 800N. (Table 9

Table 9: Group A: Load value of initial crack formation as a percentage of number of specimens.

Group	THICKNESS	500N	800N	1000N	1200N	1500N	1700N	2000N
A	**1.0**		20%	30%	40%	10%		
	Under 800N		**20%**					
	0.8	20%	40%	30%	10%			
	Under 800N		**60%**					

Group B: Class I cavity with no composite core

In the porcelain thickness of 0.8mm, only 10% of the specimens showed any crack formation at values under 800N. In the porcelain thickness of 1.0mm, no specimens showed signs of crack formation at values under 800N (see Table 10).

Table 10: Group B: Load value of initial crack formation as a percentage of the number of specimens

Group	THICKNESS	500N	800N	1000N	1200N	1500N	1700N	2000N
B	**1.0**			30%	10%	10%		50%
	Under 800N		**0**					
	0.8		10%	20%		20%	30%	20%
	Under 800N		**10%**					

It is important to note that in three cases, the initial cracks' load values were higher than the final maximum load value (Table 11).

Table 11: Specimens that registered a maximum load value lower than the initial crack formation value.

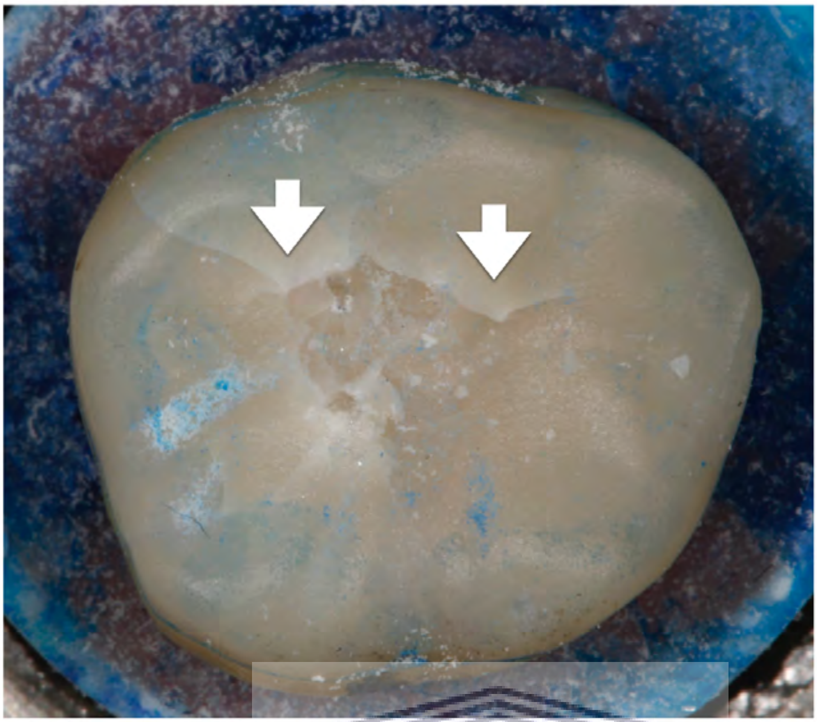
Specimen	Group	Thickness	Crack	Fracture
13	A	2	1000	380
14	A	2	500	492
37	B	2	1700	1540

1.14 Classification of mode of fracture

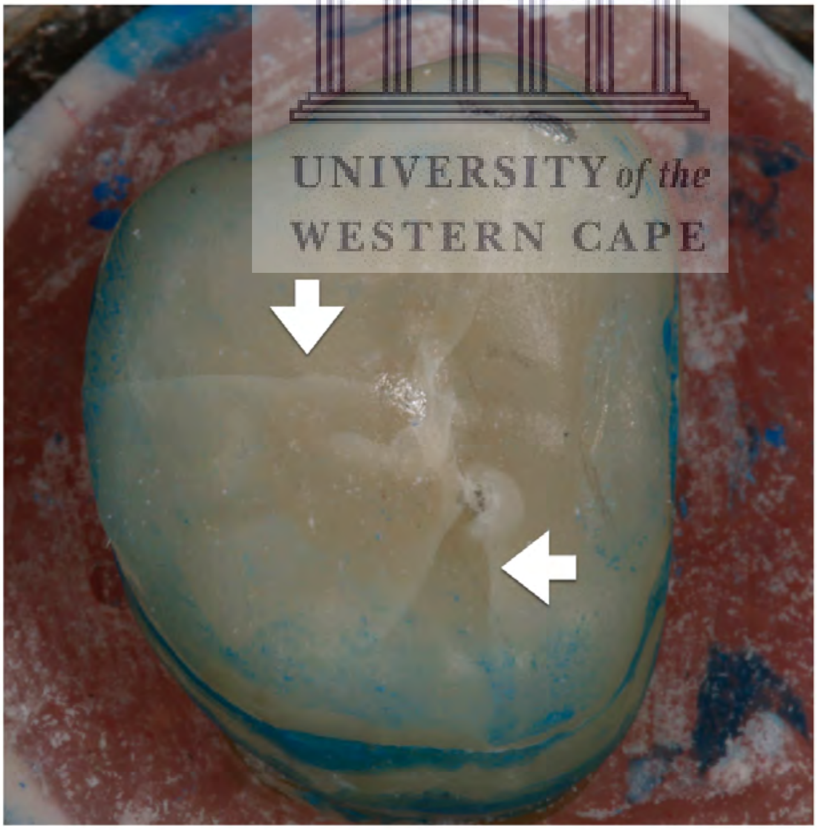
Following previous classification by Guess et al (Guess *et al.*, 2013), the final fracture patterns observed in this study were classified according to the following criteria:

I. Extensive crack formation within the ceramic;
II. Cohesive fracture within the ceramic;
III. Fracture within the ceramic and tooth structures;
IV. Ceramic and tooth fracture involving the root.

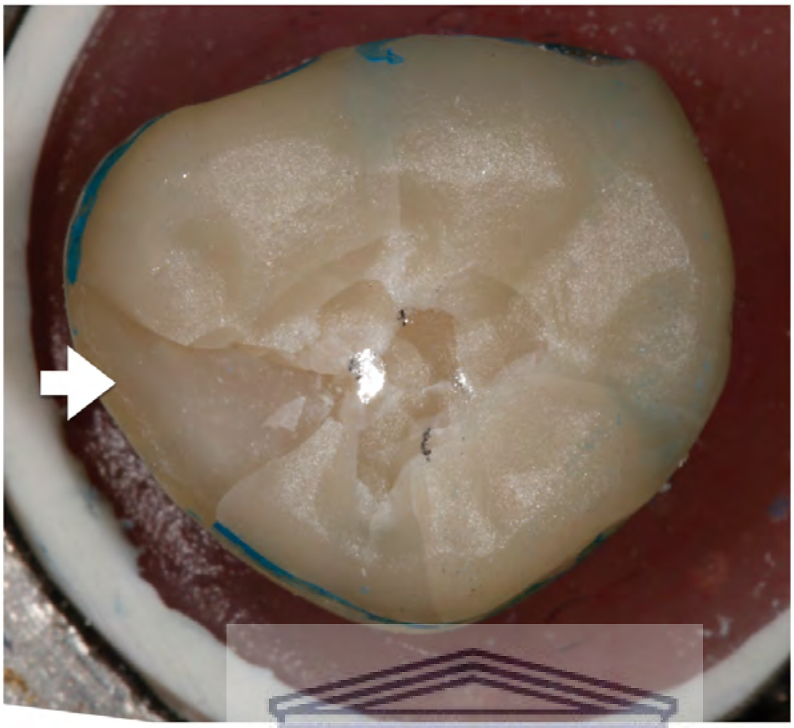
Fracture modes were further evaluated according to their restorability. All specimens with fractures that did not affect the underlying tooth structure (Groups I, II & III in classification) were deemed restorable. Specimens from group IV were classified as un-restorable(Guess *et al.*, 2014). All groups were shown as a percentage of the total number of specimens.



a) specimen with a Group I cohesive fracture of the ceramic

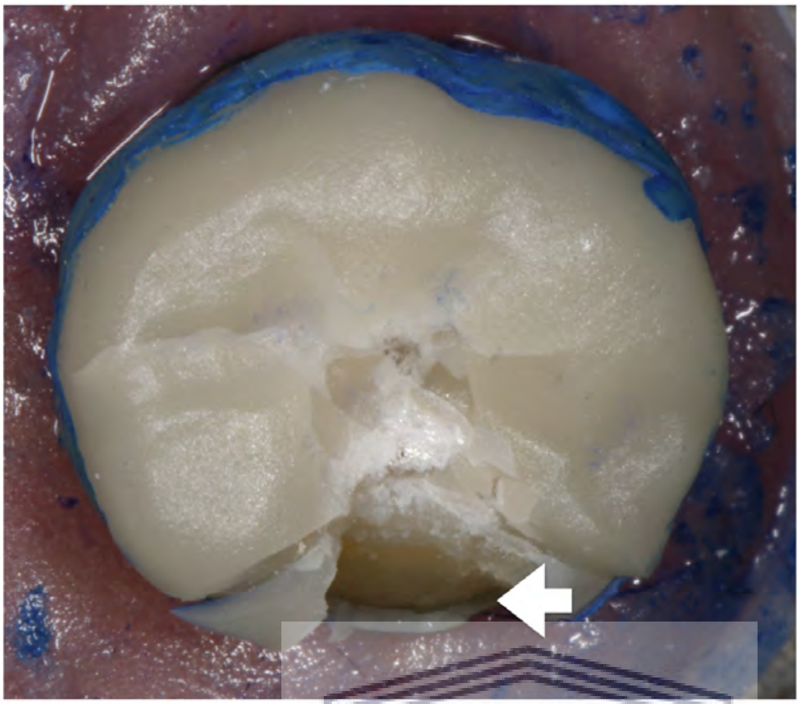


b) specimen with a Group I cohesive fracture of the ceramic

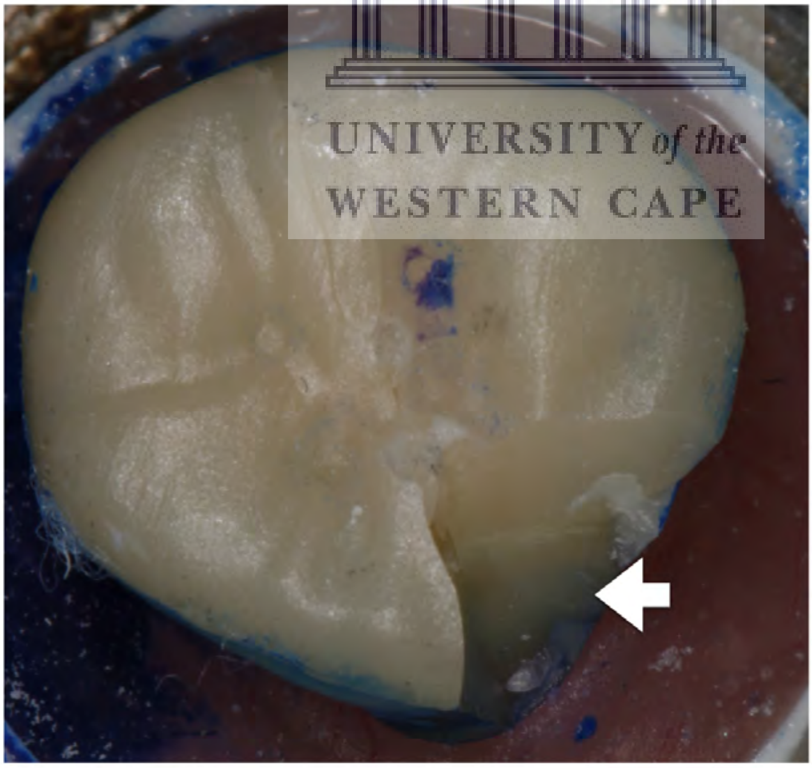


c) specimen with a Group II fracture of the ceramic that does not damage the tooth structure

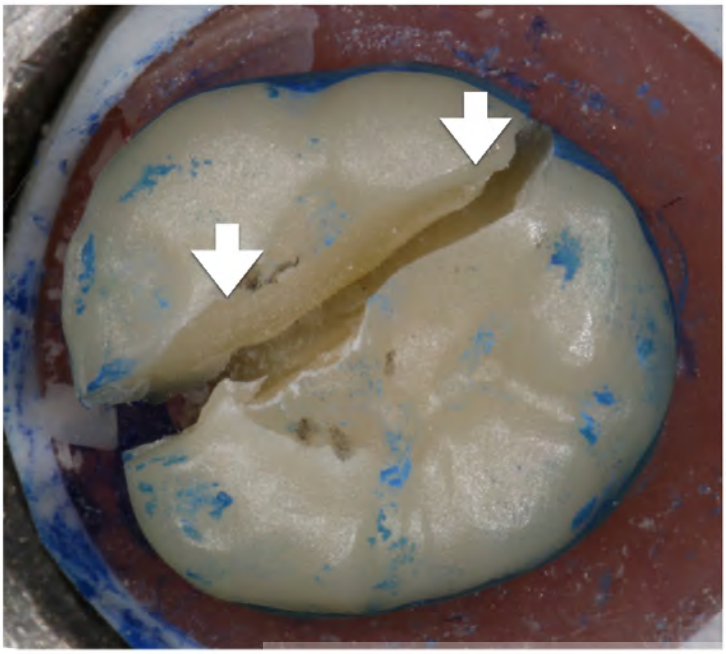
d) specimen with a Group II fracture of the ceramic that does not damage the tooth structure.



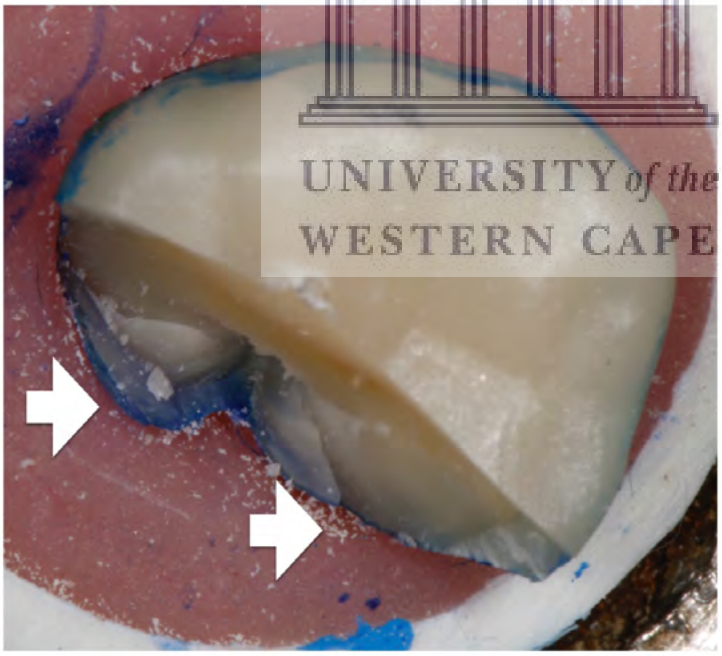
e) specimen with a Group III fracture that includes damage to the tooth structure



f) specimen with a Group III fracture that includes damage to the tooth structure



g) specimen with a Group IV fracture that includes damage to the root



h) specimen with a Group IV fracture that includes damage to the root

Figure 23: (a –h): Showing the different images of the fracture type found.

Fracture mode I (a and b). Fracture mode II (c and d). Fracture mode III (e and f). Fracture mode IV (g and h).

Group A

When evaluating the mode of fracture in the porcelain thickness 1mm, 60% of specimens had fractures limited to the restoration itself. An additional 30% were un-restorable.

In the porcelain thickness of 0.8mm, this increased to 80% of specimens with fractures limited to the restoration and only 20% were classified as un-restorable (Table 12).

Table 12: Group A - Classification of mode of fracture as a percentage of number of specimens.

Group	THICKNESS	I	II	III	IV
A	1.0	10%	50%	10%	30%
	0.8	40%	40%		20%

Group B

When evaluating the mode of fracture in the porcelain thickness 1.0mm, only 20% of specimens had fractures limited to the restoration itself. An additional 70% were un-restorable.

In the porcelain thickness of 0.8mm, the number of fractures limited to the ceramic increased to 30% of specimens, with an additional 60% being un-restorable (Table 13.)

Table 13: Group B: Classification of mode of fracture as a percentage of number of specimens.

Group	Thickness	I	II	III	IV
B	1.0	10%	10%	10%	70%
	0.8		30%	10%	60%

CHAPTER 5

Discussion

During this *in vitro* study, the ideal thickness of monolithic lithium disilicate restorations with various preparation designs were investigated. By evaluating two thicknesses of lithium disilicate with two distinct preparation designs, this study aimed to replicate the clinical situation clinicians could face when large areas of tooth structure have been lost through caries or erosion. When restoring such large areas, the clinician needs to decide on the ideal restorative thickness and technique that would best suit the clinical situation. Such an ideal thickness, or "Goldilocks" thickness of ceramic together with the ideal preparation design, would create a restoration that would withstand normal masticatory forces, but when exposed to extreme conditions, would only cause damage to the restoration, leaving the tooth structure unaffected.

When considering the "Goldilocks" thickness of the restorative and the ideal preparation design, the clinician needs to find a balance between the strength and durability of the restorative material and the strength and survival of the remaining tooth structure in the long term. Often, large amounts of healthy tooth structure are sacrificed to allow for enough restorative space to accommodate the inherent weakness of the restorative material (Dietschi & Spreafico, 2015). This sacrifice leads to a reduction in the strength of the remaining tooth, often leading to an increase in fractures that are difficult to repair, or fractures that are seen as catastrophic, leading to the loss of the tooth (Beier *et al*., 2012). Alternately, too thin a restoration will lead to a reduction of material strength with lower clinical survival rates and increased material complications (Krämer et al., 2005).

Cavity design optimization (CDO) was developed to help overcome some of the unnecessary tissue removal when creating inner-cavity designs for indirect restoratives (Jackson, 1999). Using such principals in a bio-substitutive manner (Dietschi & Spreafico, 2015), the clinician has the opportunity to maximise the strength of the restorative material while preserving the maximum amount of sound tooth structure.

Following such CDO or bio-substitutive cavity designs, current literature has investigated the ideal thickness of the restorative lithium disilicate as it is bonded to a partial resin substrate in the bio-substitutive model (Sasse et al. 2015). However, the author has not identified any research that has directly compared the use of such a bio-substitutive approach with a more traditional cavity design approach where no resin dentine-replacement is used.

To find the ideal balance and achieve the "Goldilocks" restoration, three fundamentals of minimally invasive dentistry and indirect porcelain restorations need to be considered:

- The material used for restoration
- The technique used for cementation
- The preparation design

The development of stronger particle-filled ceramics such as lithium disilicate with its strength and pleasing aesthetic properties have made these ceramics a popular restorative material in a minimally invasive protocol (Christensen, 2011). This inherent strength has a significant impact on the underlying preparation design with lithium discilicate being used more widely in a minimally invasive, partial restoration protocol (Silva *et al.*, 2012; Valenti, 2015; Rocca *et al.,* 2015).

The strength of the restorative material is also dependent on the ability to adhesively bond it to the underlying tooth structure. The use of adhesives such as "universal adhesives" incorporates the versatility of being adaptable to the clinical situation, producing excellent immediate bond strength to various bonding substrates (Wagner et al., 2014). The resin cements in turn forms a chemical bond with the adhesive, thereby generating a particularly strong bond between the tooth structure and the ceramic. Such bond increases the fracture resistance and thus the survival rate of all-ceramic restorations. Minimally invasive restorative techniques, such as non-retentive occlusal veneers, would be unthinkable without adhesive luting composites (Vargas et al., 2011).

By incorporating these popular adhesive materials and ceramics, the conservative preparation design for this study uses the CDO and a bio-substitutive approach which is based on preparation designs of similar studies by Clausen *et al*. (2010) and Sasse *et al.* (2015). A conservative preparation design with straight bevelled finish lines with soft internal angles and standardized inter cusp angle was used (Arnetzl & Arnetzl, 2009). This is supported by Clausen *et al*. (2010) who showed that marginal preparation design had no significant influence on fracture resistance. In addition, in this study a single large defect was created in the occlusal aspect of the tooth to simulate the clinical situation where large amounts of tooth structure had been lost (Figure 24 shows a clinical situation where such a defect is present).

1.15 Fracture values

Having randomly divided forty molar teeth into two groups (A and B), each group received occlusal cavity preparations simulating a Class I defect (Figure 18; a - d) to simulate clinical conditions. The specimens of group A had the Class I defect adhesively filled using direct composite material to create a conservative and uncomplicated preparation design (Figure 18; e - f). This follows the Cavity Design Optimization (CDO) principals as stated by Dietschi *et al*. (2015). In a similar study using similar preparation designs, Sasse *et al.* (2015) results suggested that this type of preparation protocol, where adhesive composite material using

CDO techniques is used, had only minor influence on the fracture resistance of the restorative ceramic.

Each group was further divided into two subgroups, each with a distinct ceramic thickness (0.7mm in the fissure and 1mm over the cusp or 0.5mm in the fissure and 0.8mm over the cusp). After static loading using a universal testing machine (Zwick Z010/TN2A, Ulm, Germany) the maximum fracture loads were evaluated. The porcelain thicknesses of 0.7 - 1mm in group A (composite core preparation) with a mean fracture values noted as 2460 Newton, were similar reported by Sasse *et al* (2015) under similar test parameters. In this current study, there was a significant difference in the maximum fracture value between the restorative thicknesses of 0.7 - 1mm and 0.5 - 0.8mm ($p < 0.05$, Kruskal-Wallis test) of Group A. This corresponds with Sasse's results which also showed similarly significant reduction in fracture values of ceramics thinner than 0.7 – 1mm when using a composite core. Our finding therefore supports the conclusion by Sasse that a minimum thickness of 0.7–1.0 mm should be maintained when a self-etching primer is used for conditioning of the tooth substrate in an occlusal veneer design restoration using lithium disilicate and CDO principals (Sasse *et al*., 2015).

The similarities between the results of the current study and those of Sasse (2015) allow us to deduce that, had the current study investigated the clinical situation where no Class I defect was present and dentine remained similar to a dental erosion lesion, the dentine core preparation would have achieved similar results to that of the composite core (with the same design). This is in accordance with the conclusions that were made by Sasse in 2015.

In addition to the preparation design in Group A (composite core preparation) this study investigated the clinical decision where CDO principals were not used, and all missing structure was replaced with ceramic only (Group B – Ceramic core. Figure 18; g - h). Such a preparation design would create ceramics with far greater thicknesses in the fissure area leaving them potentially more resilient to fracture.

When evaluating the maximum fracture values of two similar thicknesses of ceramic (1mm over the cusp and 1.7mm in the fissure or 0.8mm over the cusp and 1.5mm in the fissure) in group B (no composite core preparation) there was no significant difference noted in their fracture values ($p < 0.05$, Kruskal-Wallis test). This can be attributed to the thicker porcelain in the fissure area, that is now being filled by the ceramic (Figure 19; e – f), leading to more resilient restorations even when preparations over the cusps were reduced.

Similarly, due to the far greater thicknesses of the ceramic in the fissure area, it could be expected that the resultant restorations would produce significantly higher fracture values than that of group A. However, the current study results showed that when comparing the fracture values of the 1mm thick porcelain restoration of the two different preparation designs (Group A - 2460 Newton and Group B - 3142 Newton, refer to Table 12), no statistical significance was noted in the maximum fracture resistance ($p > 0.05$, Kruskal-Wallis test). When evaluating the fracture values of the thinner porcelain restoration of the two different preparation designs of Group A and B, a statistical significance was noted in the maximum fracture resistance ($p < 0.05$, Kruskal-Wallis test).

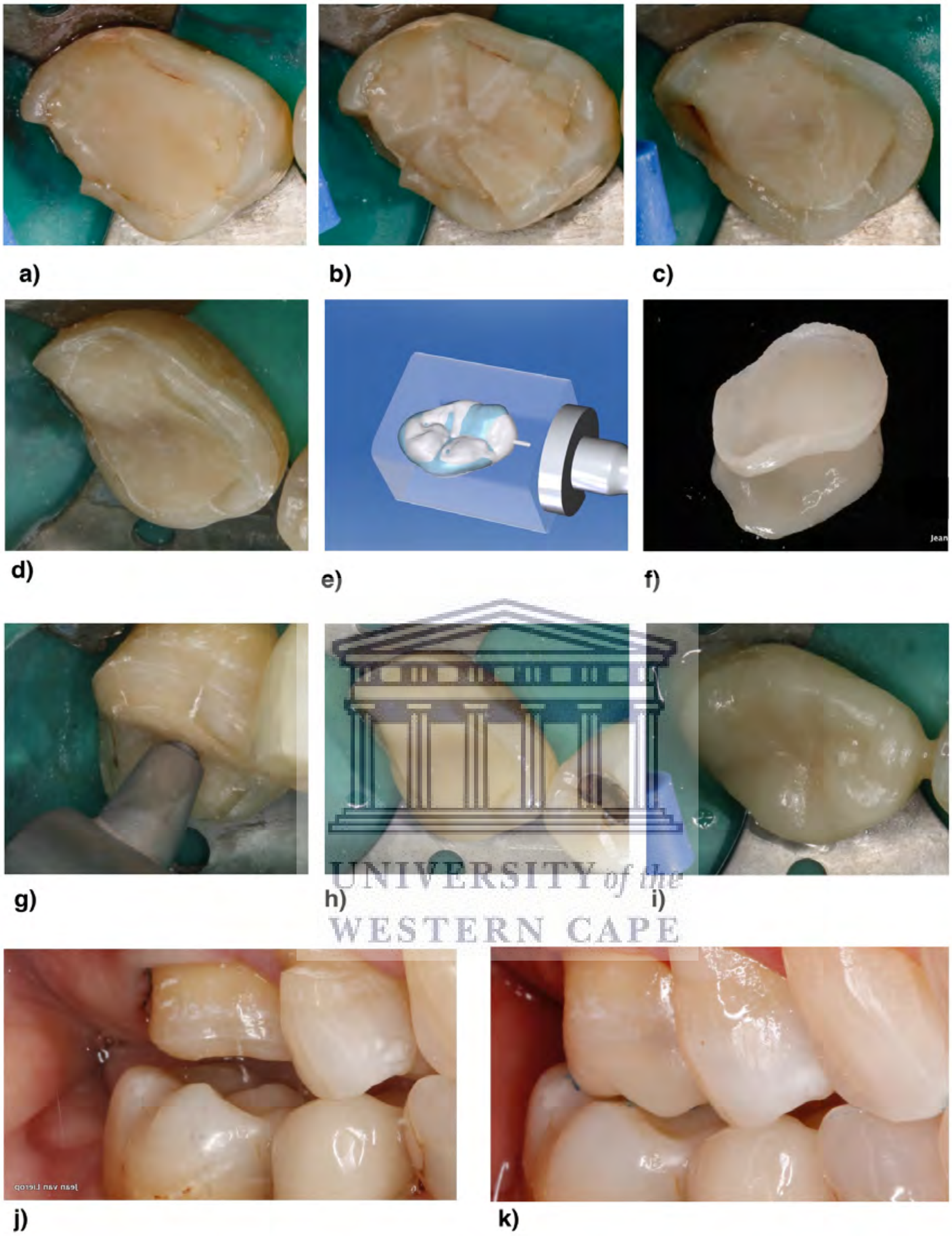
It can therefore be concluded that when using restorations of a thickness of 1mm over the cusp, the use of composite core or ceramic core would result in similar load performances. Should the ceramic be reduced over the cusp area, a ceramic core would result in higher maximum fracture values.

When using these *in vitro* results and conclusions to guide the clinical situation, one should take into consideration the bite forces experienced during mastication. As can be seen in figure 14 the results of numerous laboratory experiments that investigated the maximum bite force vary. This is due to several factors that include: subject gender and age, food type, jaw disorders, tooth quality, muscular strength, and other factors (Osborn, 1996). This reported maximum bite force generally falls within the range of 500-800 N. These maximum masticatory forces that exist during function and maximum load, contribute greatly to the fatiguing of both the restoration and remaining tooth structure. When evaluating the performance of minimally invasive lithium disilicate restorations, these maximum masticatory forces should be considered. Such values can give a better indication of the potential long-term clinical performance of the restoration and remaining tooth.

In an attempt to evaluate the impact of clinically relevant masticatory forces on the fracture resistance of the varies restoration designs, each specimen was investigated for any signs of damage at varying load intervals during the loading protocol. These load values were recorded at intervals of 500N, 800N, 1000N, 1200N, 1500N, 1700N, 2000N before maximum load was applied. All specimens that showed initial crack formation under 800 Newton were grouped together. These specimens could be seen as being at higher risk of failure under clinical load.

The resultant values indicated that in Group A (composite core), the porcelain thickness of 0.7 - 1mm had only 20% of specimens showing signs of crack formation at values under 800N. In the porcelain thickness of 0.5 - 0.8mm this increased to 60%. This could have the clinical significance that, when using a preparation design that incorporates CDO preparation techniques, porcelains thinner than 0.7 – 1mm run a higher risk of failure under clinical load. This conclusion correlates with Sasses' (2015) findings during dynamic load testing using a masticatory simulator. Here they found that only the restorations with a thickness of 0.7–1mm withstood dynamic loading unharmed. Restorations with thinner porcelain thicknesses showed increased failure under dynamic loading. Both the findings of this study and that of Sasse, support the clinical use of ceramic thickness of 1– 0.7mm when CDO techniques, in a bio-substitutive model, are used. A prediction on the remaining longevity of the restorations already showing crack formation cannot be made since no studies on this subject have been published so far.

The values of initial crack formation in Group B (ceramic core) were significantly higher than that of group A. Porcelain thicknesses of 1mm over the cusp showed no signs of crack formation at values under 800N and 50% of restorations withstood forces over 2000N. Only 10% of porcelain at thickness of 0.8mm over the cusp showed any crack formation under 800N, with 20% surviving loads of over 2000N. This supports the assumption that the thicker ceramic in the fissure area increased the strength of the ceramic creating a clinically resilient restoration.



(a - d) preparation; **(e - f)** manufacture of CAD/CAM lithium discilicate; **(g - i)** cleaning of tooth surface, application of bonding agent and cementation of restoration;
(j) - confirmation of volume of reduction to allow for a clinical sound restoration;
(k) - final result

Figure 24: Clinical situation where a reduced thickness lithium disilicate overlay was used. (Dr Jean van Lierop)

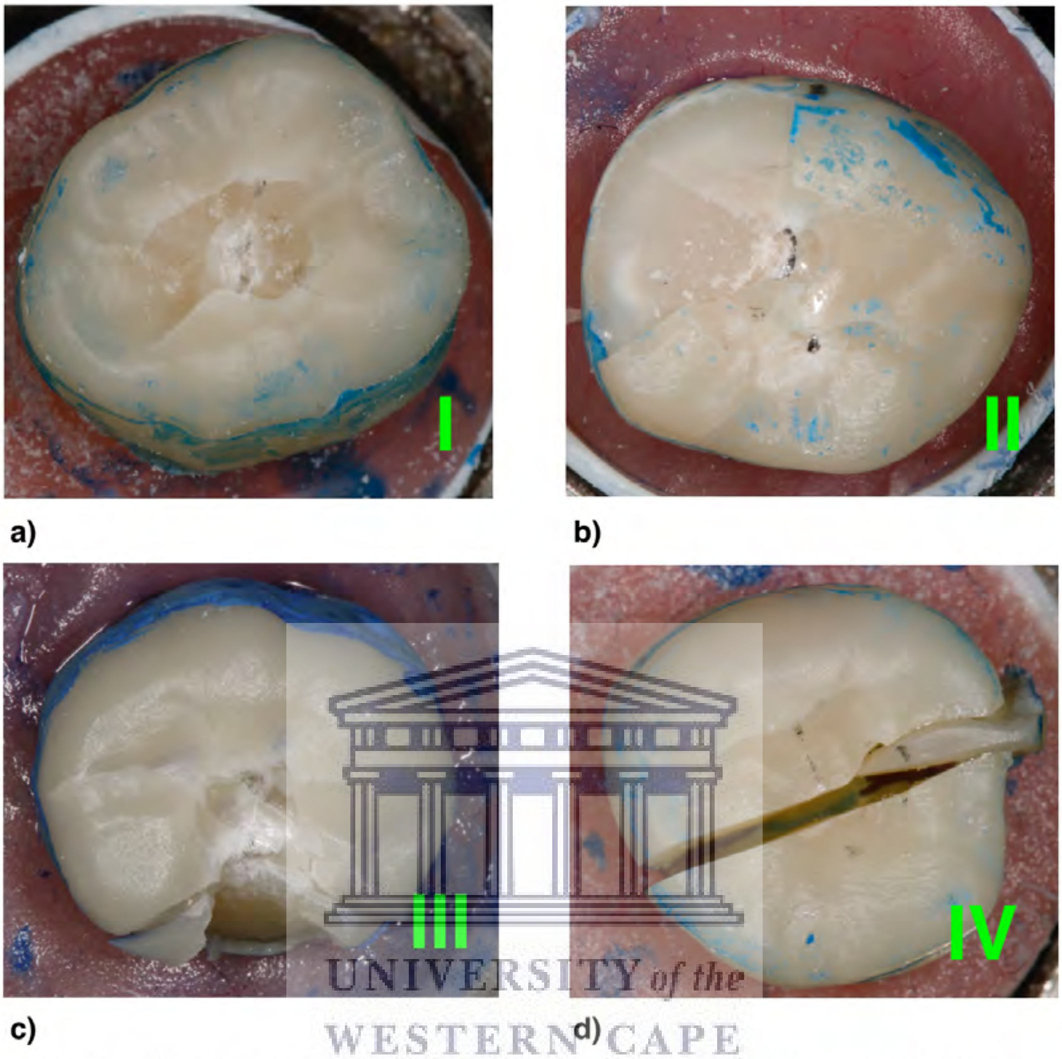
1.16 The type of fracture

When final fracture of the thin occlusal veneer restoration does occur, the type of fracture takes place is of great clinical importance. In recent studies, focus has been given to determining the mode of fracture and its impact on the restorability of the underlying tooth structure once fracture has occurred. It has been shown that thicker restoration show more catastrophic fractures with extensive damage to the underlying tooth strucre structure that is unrestorable, whereas thinner restorations generally show less damage to the underlying tooth (Guess *et al.*, 2013; Egbert *et al.*, 2015; Magne *et al.*, 2015; Sasse *et al.*, 2015a). This has a direct influence on the restorability and long term prognosis of the tooth. Image Figure 22 gives an indication of the results of some of these studies and their conclusions.

Author	Fissure thickness	Comment
Sasse M (2015)	0.7	... fractures occurred at the adhesive interface between the restoration surface and the luting composite
Guess PC (2013)	0.5	... Irrespective of preparation designs, reduced ceramic thickness resulted in fewer catastrophic failure modes
Egbert JS (2015)	0.3	... Most specimens fractured in the restoration without involving tooth structures
Magne P (2015)	0.7	...all failures were re-restorable.

Figure 25: The mode of restoration failure at various fissure thicknesses as noted in current studies

In the current study, considering the increased resilience to fracture of the thicker restorations of Group B, the current study also investigated the mode of failure that occurred. This is relevant from a clinical perspective, where the ability to restore the failed restoration would be based on the complexity of the fracture that occurred (Figure 26 gives an overview of the fracture mode classification used). Where failure modes are limited to the ceramic, renewing the restoration could readily reverse the restoration failures (Groups I & II). In contrast, failures involving the underlying tooth structure (Group III) would require further, more complex treatment, including the possibility of endodontic treatment. In some instances, catastrophic failure (Group IV), would lead to the loss of the tooth. This highlights the advantage of preparation techniques that allow for minimally invasive strategies that preserve the natural tooth structure, leaving a stronger remaining tooth and increasing its lifespan.



a- d) classification of type of fracture: **I** - extensive crack formation within ceramic; **II** - cohesive fracture within ceramic; **III** - fracture within ceramic and tooth stricture; **IV** - ceramic and tooth structure fracture involving the root

Figure 26: Simplified classification of mode of fracture

In the current study, 70% of specimens in Group A, with the porcelain thickness 0.7 - 1mm, showed modes of fracture limited to the restoration itself. These were all restorable. In addition, 30% were un-restorable. For the thinner restorations in the same group, 80% of specimens showed fractures limited to the restoration and only 20% were classified as un-restorable (table 23). These values change drastically when one looks at the modes of failure of Group B (ceramic core). Here only 20% of specimens had fractures limited to the restoration itself and an additional 70% were un-restorable. This improved marginally for the thinner porcelain thickness (0.5 - 0.8mm with ceramic core) to 30% of specimens showing fractures limited to the restoration and 60% having damage that cannot be restored (Table 23).

This drastic increase in the number of catastrophic failures found with the all-ceramic restoration correlates with previous studies that showed an increase in complex failures when larger volumes of tooth structure had been lost (Magne & Belser, 2003; St-Georges *et al.*, 2003). Such fractures have significant clinical implications, with the complete loss of the tooth being inevitable for most of these restorations.

The goal of this study was to identify the ideal porcelain thickness and preparation design that would create a clinically acceptable restorative while maintaining strong remaining tooth structure. This goldilocks thickness of ceramic and underlying preparation design, would create a restoration where clinically relevant masticatory forces do not cause damage, but under extreme conditions, the restoration would be the first point of failure. This would leave the tooth structure mostly intact and contribute to the longevity of the underlying tooth.

It is therefore important to consider what the clinically relevant strength should be. When one considers the maximum fracture resistance of unprepared natural posterior teeth to be reported at 2680N, then it is clear that maximum loads of similar values would be more than acceptable. When fracture values higher than that of the natural tooth is found, one would deduce that far greater damage would occur to the tooth structure under extreme load. This is simply due to the fact that the weaker of the two structures would fail first under load. As the restoration is often stronger than the underlying tooth structure, the tooth would be the point of failure, leading to catastrophic consequences. In addition, if the restoration shows lower maximum load values, the reduced strength of the restoration would lead to failure of the restoration itself before damage to the underlying tooth structure takes place. This would more than likely leave the tooth repairable.

Of further clinical consideration is the fatigue resistance of the restoration and preparation design. When one takes into consideration the maximum masticatory forces of 500 – 800 N, then restorations that show no signs of initial crack formation or damage at values under 800N should result in clinically lower fatigue failures. Although such an assumption should be made with caution, direct correlation could be drawn between this study's results and that of similar studies that investigated fatigue resistance.

In Group A, the mean maximum load value is recorded at 2460N for 0.7 – 1mm thick ceramic. In this group, only 30% of specimens showed catastrophic failure. In addition more than 80% of the restorations did not show signs of damage at functional loads under 800N. This is in direct contrast with the same thickness restoration of Group B (ceramic core). Here, mean maximum loads were greater (3142 N) with the resultant number of catastrophic failure being far more.

When one applies the "Goldilocks" principal of ceramic, (where a restoration is created that survives normal masticatory function, but under extreme conditions, leaves the tooth structure intact) it can be deduced that the use of a ceramic core would create a theoretically stronger restoration, but, under extreme load, could lead to more significant damage to the remaining tooth structure. When composite is used in CDO technique, a restoration thickness of 0.7 – 1mm is of similar strength than that of a restoration with a ceramic core, but the number of catastrophic failures is greatly reduced. This would lead to the conclusion that where large volumes of dentine have been lost, a composite core and CDO with a lithium disilicate restoration at thickness of 0.7 - 1mm would give the ideal balance between restorative strength and strength of the remaining tooth structure. This would lead to better long-term survival of the tooth.

CHAPTER 6

Conclusion

Within the limitations of this *in vitro* study, it was concluded that:

1. The fracture resistance of monolithic lithium disilicate with a thickness of 0.7mm in the fissure and 1mm over the cusp, is significantly higher in fracture resistance than the thinner restorations of 0.5mm in the fissure and 0.8mm over the cusp. This can therefore be recommended as a minimum thickness of occlusal veneer designs when using adhesive cementation with a universal adhesive and selective etching.
2. With restoration thicknesses of 1mm over the cusp, the preparation design does not have a significant influence on the maximum fracture strength.
3. When evaluating the mode of failure of restorations and remaining tooth, restorative designs that make use of cavity design optimisation (CDO) principals using direct composite restorations, show less complicated fractures and may contribute to the longevity of the underlying tooth.
4. When using ceramic to restore defects where large volumes of dentine has been lost, a lithium disilicate restoration with thickness of 0.7–1.0 mm in combination with the use of cavity design optimisation (CDO) and adhesive cementation with a universal adhesive and selective etching, can be recommended for use.

CHAPTER 7

Limitations

- This is an *in vitro* study and may have limitations when translated to the clinical situation.
- This study used static loading and not dynamic loading, as may be the case in the oral environment.
- Factors in the mouth, such as the impact of musculature, the patient's chewing patterns and occlusion, may all impact on fracture pattern.
- Only one porcelain material was tested in this study. Further investigation is needed on the use of other materials that could show similar results.
- Further clinical trials are required to correlate these *in vitro* results.

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APPENDIX 1

UNIVERSITY *of the*
WESTERN CAPE

Oral & Dental Research Institute
Faculty of Dentistry and WHO Oral Health Collaborating Centre
University of the Western Cape
Cape Town

Patient Information Sheet to be given to the patient to take home

I, Dr Jean van Lierop am a qualified dentist involved in research and training at the University of the Western Cape, Faculty of Dentistry.

I am doing research on porcelain restorations.

After the removal of your teeth, they are either discarded or given to the students to practice on. I wish to use your teeth to be able to determine the ideal thickness and strength of porcelain restorations.

Donating your teeth in the study is on a voluntary basis. Donating your teeth for this study or refusing to participate will not harm or prejudice you in any way. The teeth supplied to me will not have your name on it as well as I will not be able to identify you in any way. Upon completion of this study the teeth will be discarded.

Participating in the study will definitely benefit future studies and will add to our existing pool of knowledge. All information will be kept strictly confidential.

Thanking you.

Dr Jean van Lierop
Researcher
Oral & Dental Research Institute
Oral Health Centre Tygerberg
Contact details: Tel: (021) 937 3090
Mobile: 072 220 3718

If you have any other queries, you are welcome to contact the head of the research institute, Dr D. Moodley at 021 937 3090

I, (Patient name)..., fully understand the information supplied to me by Dr Jean van Lierop in this information sheet

Signature: ....

Date: ....

APPENDIX 2

UNIVERSITY OF THE WESTERN CAPE/PGWC

FACULTY OF DENTISTRY

PATIENT CONSENT TO USE EXTRACTED TEETH

Surname:	Date of Birth:
Name:	File No:

I,... hereby give consent to use my/my child's extracted teeth. I understand that the teeth concerned have no diagnostic value and would normally be discarded. I understand that the teeth will be anonymous at the point of collection and completely unidentifiable in the laboratory, therefore my consent cannot be withdrawn as the teeth cannot be traced back to me. I have been informed that the teeth may be stored for as long as needed in a secure environment. When discarded, they will be discarded according to Department of Health protocols.

I hereby give consent for my extracted teeth to be used for education, teaching, training and approved research purposes. The research performed may be any type of unspecified research, but DNA will not be used and any extracted cells/tissue will not be immortalized to create cell lines. I understand that my consent or refusal will in no way affect my /my child's dental care.

Patient Signature: .... Date:...

Parent/Guardian (if patient under 18 years) Name: ....

Signature... Date: ……..

Child assent (7-17 years): ………..……… Date: …………….........................

Witness Name & Signature............................. Date: ………………......................

Prepared by Dr Jean van Lierop (June 2016)