Tooth Preparation

measuring, understanding, and reporting tooth preparation and its influence on the fracture of all-ceramic crowns

Janine Tiu

A thesis submitted in fulfilment of the requirements for the degree of

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Tooth Preparation - measuring, understanding and reporting tooth preparation and its influence on fracture of all-ceramic crowns.

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Abstract

Tooth preparation for a single complete crown is a fundamental principle in fixed prosthodontics. The geometry of the preparation is clinician-controlled and accepted by the dental community to affect the retention, displacement resistance, and survival potential of a crown. Crowns are routinely placed by clinicians, therefore investigation into the geometry of tooth preparations and its influence on prosthodontic success is important and is of interest to clinicians.

With many geometrical, biological, and technical variables contributing to the clinical success of a dental crown, developing a complete understanding into this complex system is a lifelong challenge. This thesis focuses on the total occlusal convergence angle - the parameter most studied and solely under the control of the clinician. The three objectives of this thesis are:

1. To develop a validated objective method for measuring crown preparation geometry;
2. To report on the geometry of tooth preparations by dentists; and
3. To understand the importance of the total occlusal convergence angles by understanding their effects on fracture mechanisms and hoop stresses.

This thesis begins by investigating methods used to measure tooth preparations. By identifying subjective problems in existing methods, a new method was created and further developed into a *measuring* program. The measuring program was used in a multipart study to *report* the geometrical parameters of tooth preparations prepared by general dentists. Finally, the convergence angle measurements were taken further in an

in vitro study to investigate and *understand* its influence on hoop stresses by an axial compressive force and understand this effect on the fracture of glass ceramics.

The systematic review on measuring methods found that the majority of studies measured the convergence angle in two cross sections. Meta-analysis could not be performed as the methods were too varied. The study highlighted the need for a universal standardised measuring method. A new method was proposed and a small validated study carried out. The method was found to be reproducible and less subjective than all previously reported methods.

It was found that convergence angles of tooth preparations by general dentists were greater than the recommended values and marginal widths of preparations fell short of recommended values. Measuring the parameters enabled the calculation of theoretical retention and resistance values of the tooth preparations. Based on the study, the majority of preparations with large angles did not show any resistance form.

Large convergence angles demonstrated a greater mechanical advantage when axially loaded *in vitro*. An extended finite element model was validated by the experimental model to generate a fracture initiating from the inner surface propagating to the outer surface in alignment with clinical failures.

This study showed that the recommended convergence angle may not be as responsible for clinical success as previous reported. A thorough understanding on each isolated parameter and in combination is needed before the clinical survival can be attributed to the clinician-controlled geometry.

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List of publications

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Refereed journal articles (n= 7)

2016 Tiu J, Yu J, Chin E, Hung T, Lin T, Schwass D, Al-Amleh B. Feasibility study on the Effectiveness of Preparations Assessment Software. Accepted at the Journal of Dental Education (August Issue)

2016 Tiu J, Lin T, Al-Amleh B, Waddell JN. New Zealand Dental Students Dental Crown Preparations. J Prosthet Dent 2016 EPub

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2014 Tiu J, Waddell JN, Al-Amleh B, Swain MV. Total Occlusal Convergence and Margin Design in Relation to Survival of Glass-Ceramic crowns: a review. Current Research in Dentistry 2014, 5(2): 10.16 DOI: 10.3844/crdsp.2014.10.16.

2014 Tiu J, Waddell JN, Al-Amleh B, Jansen van Vuuren WA, Swain MV. Coordinate Geometry Method for Capturing and Evaluating Crown Preparation Geometry. J Prosthet Dent 2014;112:481-7.

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Town, South Africa, June 2014. J Dent Res 93 (Spec Iss B):249, 2014 (www.iadr.org)

2013 Tiu J, Waddell JN, Al-Amleh B, Swain MV. Capturing and Evaluation Crown Preparation Geometry. 2nd Meeting of the International Association for Dental Research Asia Pacific Region (IADR-APR), Bangkok, Thailand, August 2013. J Dent Res 92 (Spec Iss B):688, 2013 (www.iadr.org)

Conference contributions (n = 1)

2014 Tiu J, Al-Amleh B, Waddell JN, Duncan WJ. Evaluating clinical molar preparations: Using the Coordinate Geometry Method. Poster session presented at the Division of Health sciences Research Forum: Learning Different Research Languages, Dunedin, New Zealand.

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1. Tiu J, Tiu J, Al-Amleh B, Waddell JN. Preppr™ – Analytical Software for Measuring Dental Crown Preparations.

2. Tiu J, Al-Amleh B, Zhang Z, Waddell JN, Li Q, Swain MV, Duncan WJ. Experimental, Analytical, and Numerical Analysis of Convergence Angles in Crown Preparations.

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01

Introduction

1.1 Introduction

Tooth preparation principles continue as a fundamental educational focus in fixed prosthodontics. Every day, clinicians employ these principles to maximise the retention and resistance and in turn, the longevity of the resulting crowns. The tooth itself is irregular in geometry with different shapes in different planes (figure 1.1). Differences in tooth structure intra-arch, inter-arch, and between individuals, combined with the many controllable parameters that comprise the geometry results in a factorial amount of tooth preparation configurations.

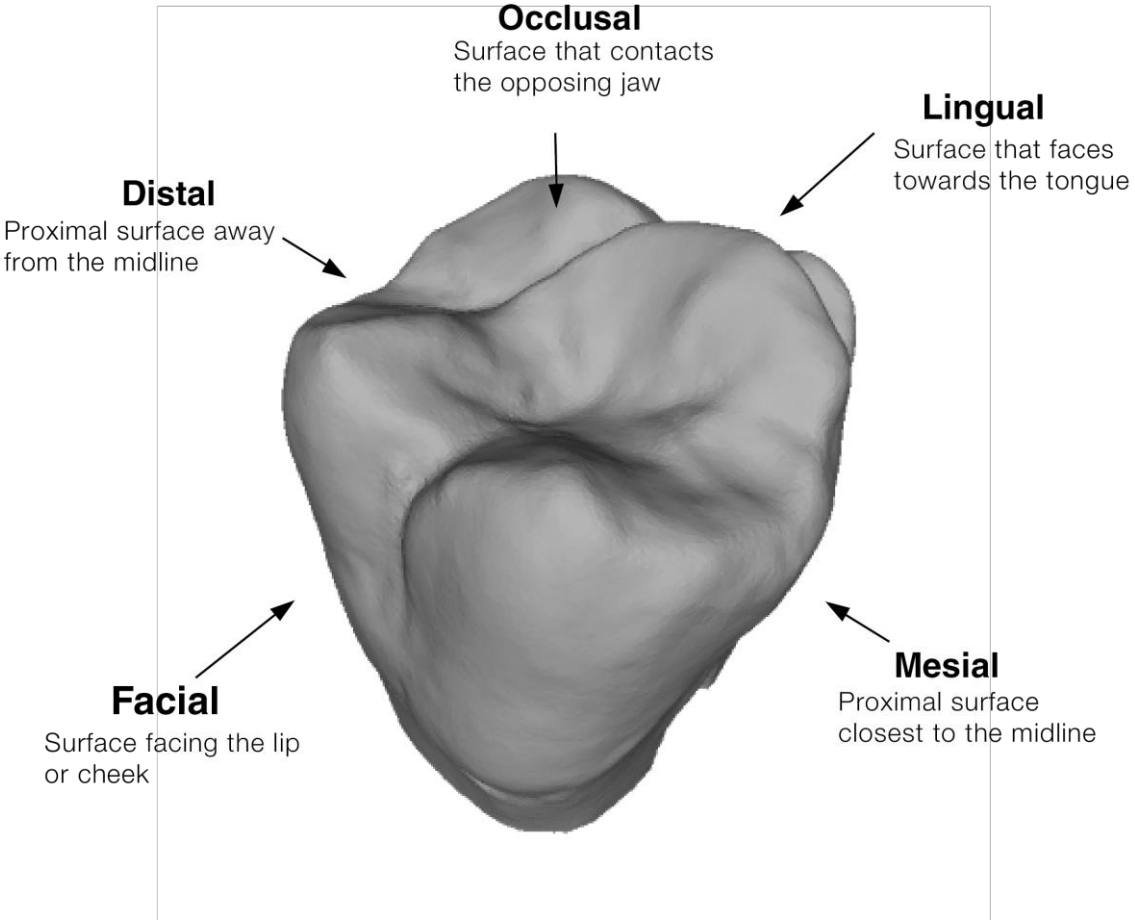


Figure 1.1 Terminology for tooth planes used in this study

As an aesthetic material, all-ceramic complete crowns are increasingly common prosthodontic materials of choice. Ceramics are subject to specific preparation guidelines which are based upon the foundation of recommended values from complete-metal and metal-ceramic restorations. Technological progress has also been seen in dental luting/bonding systems, and while earlier restorations were commonly luted with zinc phosphate cements, many all-ceramic restorations are now luted with the much stronger resin cements.

A dental crown can be simplified to a geometric cylindrical form, and as the largest principle stresses in cylinders, induced hoop stresses arising from the cementation

surface can often lead to the bulk failure of ceramic crowns. The magnitude of hoop stresses can depend on the shape configuration of the preparation geometry.

Clinical studies evaluating the longevity of restorations as a function of preparation design have never been trialled, yet manufacturers are recommending very specific guidelines on axial wall convergence and marginal widths. Without studies reporting the geometric values, it is unknown as to the condition and quality of preparations for the crowns being placed in patients every day. The problem may lie in the fact that there has not been a universally accepted means to measure these geometric parameters and there is a possibility that many clinicians are unknowingly over-preparing or under-preparing teeth for complete crown restoration.

With this possibility, preparation guidelines may not play such an important role as previously reported. Therefore, how important are these guidelines and what role do they play? Can the manufacturer's recommendations and the theories for maximising retention and resistance be negated? These questions form the basis of this study.

1.2 Aims and objectives

1. To develop a validated objective measuring method for measuring crown preparation geometry;

2. To report on the preparation geometry of tooth preparations by dentists;

3. To understand the importance of the total occlusal convergence angles by understanding their effects on fracture mechanisms and hoop stress in an all-ceramic restoration analogue.

1.3 Organisation and limitation of scope

The work in this study is presented in two parts. Beginning with a review of the literature, a large focus is placed on measuring methods and developing a validated methodology for measuring tooth preparation geometry with this section culminating in measuring tooth preparations by general dentists and quantifying the retention and resistance which has previously remained an unpractised theory. Part 2 investigates the most important tooth preparation geometric parameter; the total occlusal convergence angle, and involves an in depth investigation on the the convergence angles role and fracture mechanics using a range of analyses. This study does not include investigation into preparation grooves, differences between restoration materials, the effects of cement, and although the method can be extended to measure more tooth preparation parameters, this study is limited to margin widths, height, and convergence angles in two planes.

The study includes a series of academic papers both published and in preparation. Some of these papers are inserted in entirety and some are included in parts. This accordingly leads to a slight repetition in defining acronyms and in the introduction sections. Author contribution for all manuscripts include undertaking the experiments, collecting the data, analysing, collating, and writing. Co-authors provided guidance in analysing and final drafts.

Chapter 2 introduces and reviews the relevant literature on all-ceramic materials, tooth preparation principles, and clinical studies. This chapter includes part of a published review article on the clinical survivability of all-ceramic single crowns in relation to preparation parameters.

Chapter 3 is a published systematic review on clinical crown preparation geometry and the associated measuring methods. It identifies, organises, and critically appraises the previous measuring methods that have been used to measure the preparation geometry.

Chapter 4 is a published manuscript outlining a new theory for objectively measuring the crown geometry.

Chapter 5 takes the ideas presented in chapter 4 and develops the theory into a workable software. This includes the mathematical background and examples if its use.

Chapters 6 is part 1 of a published study which uses the methodology and applies it large scale on a study measuring dental crown preparations by New Zealand general dentists. This presents the first time a validated method has been applied to general dentist crown preparations with many important geometric parameters reported.

Chapter 7 is part 2 of a published study which takes some of the values found in the study described in chapter 4 and uses them to determine the retention and resistance of a crown based on previously described theories. These theories have been introduced as a way to quantify the retention and resistance and the following survival potential of dental crowns but have never been applied.

Chapter 8 is the conclusion of Part 1. It addresses the key findings and implications of the software development leading to questions answered in Part 2.

Chapters 9 – 10 is Part 2 of the study. It presents an investigation into the effects of the total occlusal convergence angle of a complete crown. An *in vitro* test was carried out on simplified glass crowns looking at three different taper values based on a range of critereon established in Chapter 7 and 8, whilst removing other parameters that may have an effect on its strength. An analytical model was developed and adjusted to determine the circumferential stresses and to investigate the theoretical stress at different areas of the specimen. Finite element methods were employed to model the experiment and after validation, additional variables were investigated. Finally, fracture patterns were closely studied from the experimental models and further validated with an extended finite element model.

Chapter 11 summarises the studies presented in this thesis as well as the conclusions, contributions, and suggestions for future investigations.

Part 1

02

Review of the literature

This chapter introduces important concepts of tooth preparations and current knowledge related to Part 1 of the thesis. This includes an introduction of dental ceramics, tooth preparation principles, and review of clinical studies on the survivability of single all-ceramic crowns.

2.1 Dental ceramics

Ceramics in dentistry are common prosthodontic materials used for crowns and bridges. Ceramics is a name loosely given to a group of materials generally characterised by high melting temperatures, high modulus of elasticity, poor conductivity and poor ductility (McLean & Hughes, 1965).

Dental ceramics have come a long way from early uses of glass forming and pottery. Increased knowledge and technological advances continue to drive the development of dental ceramics capable of matching natural dentition in aesthetics and strength. Classification of dental ceramics fall under three categories (Gracis et al., 2015):

1. Glass-matrix ceramics
2. Polycrystalline ceramics
3. Resin-matrix ceramics

Characterised by their microstructure, feldspathic glass-matrix ceramics have an amorphous glass content and are therefore presents itself as the most aesthetic. With the lack of a crack inhibiting crystalline structure, these ceramics are also susceptible to fracture and can also be considered the weakest dental ceramic materials.

Glass-matrix ceramics can be further subcategorised into synthetic and glass-infiltrated content. Here, the structures contain a crystalline structure, or are a network of both glass and filler crystals. This group encompasses a large range of materials of varying strengths. Many of which provide excellent strength and aesthetics allowing for monolithic restorations.

The polycrystalline ceramics are considered the strongest materials with very high flexural strength and fracture toughness values. They do not contain any glass and are the least aesthetic. Polycrystalline dental ceramics often comprise the substructure of dental restorations while gaining aesthetic acceptance by porcelain veneering.

Resin-matrix ceramics are more recent materials composing of an organic matrix filled with ceramics. The resin content allows the properties of the material to resemble dentine.

2.1.1 Glass-ceramics

Glass-ceramics in dentistry is an umbrella term for a wide range of restorative materials. These materials are composed of differing glass-crystalline structure ratios in attempts to create the ultimate strength-aesthetic restoration.

The first commercially available glass-ceramic was introduced in the 1950s by Corning Glass Works (Dicor®). The glass matrix was processed by the lost-wax technique, which was then heat-treated for controlled nucleation of various forms of mineral silicates or mica. The crystalline structure improved the strength and toughness of the glass while maintaining its aesthetics (Kelly et al., 1996; Helvey, 2010).

In the 1980s, leucite crystals were added to feldspathic porcelain to raise the coefficient of thermal expansion (CTE) to match metals in metal-ceramic restorations. The leucite crystals reinforced the porcelain and acted to slow crack propagation. The fabrication of these materials were similar to the lost wax technique, except ceramic ingots were pressed into the mold. Majority of failures were seen in the posterior region (Kelly et al., 1996).

A novel group of materials were introduced by VITA towards the end of the 1980s. These materials consisted of a porous alumina core infiltrated with glass. Subsequently, to increase translucency, alumina was replaced with spinel ($MgAl_2O_4$) and to increase

strength, a proportion of the alumina was replaced with zirconium oxide (Kelly & Benetti, 2011).

Lithium disilicate as a strengthening crystalline structure was first introduced in 1998 as Empress 2 (Ivoclar Vivident, Liechtenstein) and re-emerged again, in 2006 as IPS e.max (Ivoclar Vivident, Liechtenstein). The flexural strength of this material is 350-450MPa and is higher than any of the leucite reinforced glass-ceramics. It is fabricated either by pressing or CAD/CAM and is indicated up to 3-unit anterior bridges.

In the present day, the survival of lithium disilicate glass-ceramics have been well documented and have been claimed to be comparable to the 'gold standard' of metal-ceramic restorations when placed in appropriate clinical situations (Sailer et al., 2015). Glass-ceramics continue to be an area of development as more materials are continually being introduced, notably the new classes of zirconia-reinforced lithium silicates (ZLS). The acceptability of these materials will depend on long-term clinical studies. A selection of the materials is shown in Table 2.1.

Table 2.1 A selection of the commercial glass-ceramics

Ceramic	Crystalline Structure	Fabrication	Manufacturer
Dicor	Tetrasilicic fluormica	Lost wax	Dentsply
Cerestore	Alumina-magnesia spinel	Lost wax	Coors Biomedical
Empress 1	Leucite	Pressable	Ivoclar Vivident
OPC	Leucite	Pressable	Pentron
IPS Empress 2	Lithium disilicate	CAD/CAM	Ivoclar Vivident
IPS e.max	Lithium disilicate	CAD/CAM	Ivoclar Vivident
Suprinity	Zirconia lithium silicate	CAD/CAM	VITA Zahnfabrik
Celtra Duo	Zirconia lithium silicate	CAD/CAM	Dentsply

2.2 Tooth preparation principles

Early records for preparing a tooth for a complete crown date back to the late 1800s, when Charles Henry Land proposed for the preservation of tooth structure in his porcelain jacket crowns. This was in contrast to earlier restorations secured by the use of posts or 'pivots.' The principles he described remain fundamental in maintaining mechanical, aesthetical, and biological advantages (Land, 1988) This section briefly describes the principles of tooth preparations for fixed prosthodontics.

2.2.1 Preservation of tooth structure

Preserving the existing tooth structure has many advantages. It is recommended that sound tooth structure should not be unnecessarily sacrificed, but instead maintained for retention and pulpal vitality. The amount of tooth structure removed is governed by tooth preparation guidelines depending on the type of restoration and material (Shillingburg et al., 2012).

2.2.2 Retention and resistance

Retention is defined as the prevention of dislodging forces along the path of insertion, whereas resistance is defined as the prevention of dislodging forces along any other path other than its path of insertion (Shillingburg et al., 2012).

Retention and resistance are related and cannot regarded separately. These important principles play a vital role in keeping the restoration on the tooth. They are primarily affected by the geometry of the tooth preparation – including the axial height, the total

occlusal convergence angle (TOC) and the substitution of internal features (Shillingburg et al., 2012).

The TOC remains as the most important clinician-controlled geometric parameter in crown preparations. It is defined as the sum angle of two opposing axial walls and has been recommended from as low as 2 degrees to 20 degrees (figure 2.1) (Glossary of Prosthodontic Terms, 2005). An in depth review on this parameter and its recommended values are presented in chapter 3.

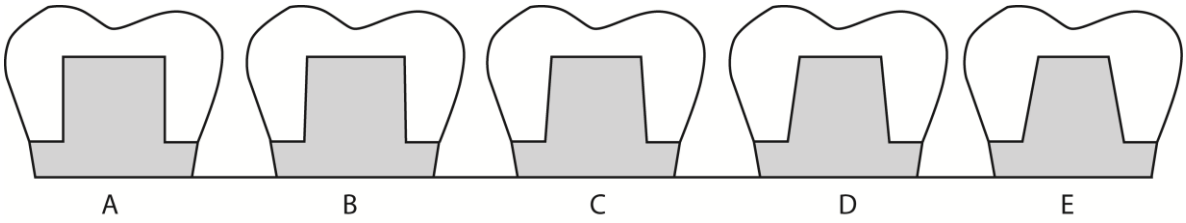


Figure 2.1 Cross-sectional view of molar crowns with a range of TOC angles; a – parallel, b – 2 degrees TOC, c – 5 degrees TOC, d – 10 Degrees TOC, e – 20 degrees TOC

2.2.3 Structural Durability

In order for the crown to fulfil its function, the preparation must be structurally durable and withstand the masticatory forces in the mouth. This is determined by the minimum bulk thickness of the material for occlusal and axial reduction, as well as creating a bevel on the functional cusp (figure 2.2) (Willey, 1956).

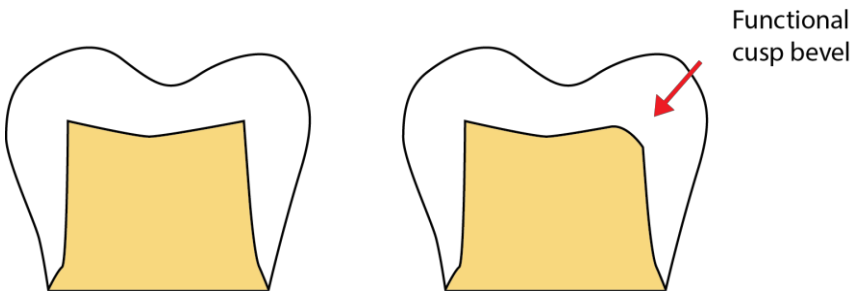


Figure 2.2 Preparation without a functional cusp bevel (left), preparation with functional cusp bevel (right).

2.2.4 Marginal integrity

The margin of the restoration is the surface interface where the crown meets the tooth structure. This area is located gingivally and therefore close adaptation is needed to inhibit biologic failures and prevent marginal chipping. The configuration is determined by the location and the material choice and has gone through a number of different design recommendations as shown in the literature (Goodacre et al., 2001). The mechanical properties of metals allow for a thin minimum thickness in the marginal area leading to past recommendations of feather-edges and bevelling (Rosner, 1963). These margin configurations were technically difficult to fabricate and if inadequately produced, led to biological failures. Currently, chamfers are recommended for all-metal restorations. Metal-ceramics require greater bulk for aesthetics and strength of the ceramic and the configuration takes into account a collar or collarless design, chamfer or shoulders are recommended for metal-ceramics with rounded internal line angles to eliminate sharp angles as illustrated in figure 2.3 (El-Ebrashi et al., 1969; Farah and Craig, 1974; Goodacre et al., 2001).

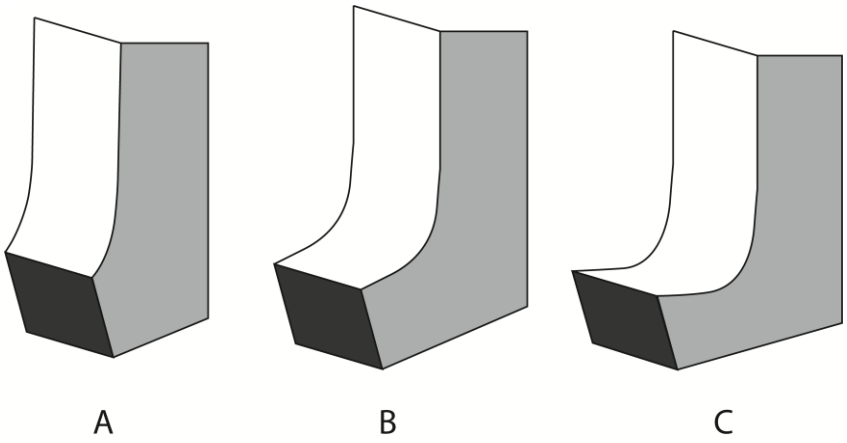


Figure 2.3 Types of margin designs; A– Feather-edge margin, B – Chamfer margin, C – Shoulder margin

All-ceramic crowns require greater care in the marginal area as ceramics are brittle in nature and are less forgiving than malleable metal materials. Margins must be smooth as sharp line angles create stress concentration sites. Sufficient bulk support of ceramic is needed, therefore smooth chamfers and shoulders are recommended (Goodacre et al., 2001).

2.2.5 Preservation of the periodontium

Preserving the periodontium is largely dictated by finish line placement. Finish lines placement are not recommended subgingivally where there is a higher chance of inflammatory response. The finish line should be smooth and exposed enough for cleaning maintenance (Shillingburg et al., 2012).

2.3 Review on clinical studies

This section is a published literature review (*Current research in dentistry)* on the total occlusal convergence and margin design in relation to the survival of glass-ceramic crowns.

2.3.1 Introduction

There is a growing interest and demand for all-ceramic materials as single crown restorations. Underlying the crown are the fundamental foundations of tooth preparation principles which aim to maximise the retention and resistance and in turn, the survivability of the resulting crown. The retention prevents the dislodgment of the restoration by forces parallel to the path of insertion and resistance prevents the

dislodgement of the restoration by oblique and occlusal forces (The Glossary of Prosthodontic Terms, 2005).

Restorations are exposed to a range of masticatory forces in the oral environment and as a result, restoration fractures and crown loosening are common failures observed (Walton et al., 1986; Wiskott et al., 1996; Pjetursson et al., 2012). Such failures are often attributed many factors including the retention and resistance factors of the system.

The governing geometric parameters contributing the retention and resistance in a preparation is namely the Total Occlusal Convergence (TOC) angle, the margin design and the abutment height. The recommendations for these parameters have somewhat remained unchanged from conventional metal and metal-ceramic crowns. The TOC is recommended to be as small as possible and the abutment height is recommended to be as tall as possible (with enough spacing for the restoration).

The TOC angle is the sum angle of the two opposing axial walls in the preparation. This geometric feature has been long and extensively studied in the literature with early laboratory studies. Prothero (1923) indicating a convergence angle range of 2-5°C, Jorgensen (1955) experimentally found maximum tensile retention at 5°C and many others (Kaufman et al., 1961; Tylman, 1965; El-Ebrashi et al., 1969a) all recommending similar TOC values. Later, clinical studies proved this minimal TOC angle was hard to achieve (Eames et al., 1978; Mack, 1980; Owen, 1986). Ohm & Silness (1978) tested dentistry students in their final year and found the TOC angles for vital teeth ranged from 19°C to 27°C. Other studies testing students and practitioners (Leempoel et al., 1987; Nordlander et al., 1988; Noonan & Goldfogel, 1991; Annerstedt et al., 1996; Ayad et al., 2005) all reported higher convergence angles showing discrepancies between recommended and actual values carried out in practice.

The margin design is the only parameter which is material dependent as it directly affects the shape and amount of bulk material. Early designs were based on requirements for complete metal or metal-ceramic crown restorative materials. The

malleable property of the metal, especially noble alloys meant the margin designs were more forgiving. An excellent fit could be achieved by burnishing down the material to the finish line with thin feather-edge or bevel-edge margins (McLean et al., 1979). Although feather-edge designs have been used with stronger and tougher zirconia crowns (Schmitt et al., 2010), glass-ceramic restorations require thicker margins and only specific shaped chamfers and shoulders are indicated (Rosenstiel et al., 2006). Gavelis et al. (1981) found a 90° shoulder margin had the best seating. Theoretically, for glass-ceramic restorations any deviations from the chamfers and shoulders to bevel-like margins would compromise the structural integrity and introduce uneven force distribution when axially loaded, which could lead to a weaker structure and ultimately failure originating from the margin. The manufacturer suggests a margin width of at least 1.0-1.5 mm with smooth internal lines to reduce potential for crack propagation.

Survivability of crowns cannot be exclusively attributed to a single factor as the factors affecting the survivability of glass-ceramic single crowns are multifaceted. It is suggested that core design plays an important role in survivability, although the extent of this is still unknown (Goodacre et al., 2001; Rekow et al., 2011). Preparation geometry parameters have been universally accepted as factors that affect retention and resistance and may contribute to the clinical longevity of a single crown. This review aims to report on preparation geometry parameters and their relation to crown failures in complete glass-ceramic clinical studies.

2.3.2 Methods

An electronic search of MEDLINE and PubMed was conducted in February 2013 to identify the clinical performance of glass-ceramic crowns in relation to the TOC and margin design published between 1986 and January 2013 with the following expanded search terms:

“glass ceramic” AND “margin design”

"glass ceramic" AND "crown preparations"

"glass ceramic" AND "margin failure"

An additional manual search was conducted through the literature to identify clinical trials that may not have been listed on MEDLINE/PubMed. The articles were chosen according to the inclusion and exclusion criteria in Table 2.2.

Table 2.2 Inclusion and exclusion criteria

Inclusion Criteria	**Exclusion Criteria**
English language	Case reports, *in vivo* studies
Prospective or retrospective clinical study focused on all-ceramic crowns	Studies only on PFM, metals, inlays, onlays, veneers, partial crowns, bridges, fixed partial dentures (FPD)
Studies using leucite or lithium disilicate reinforced glass-ceramic	Animal studies

The keyword search yielded an accumulative 483 articles from which titles, abstract and some full texts were screened according to the inclusion and exclusion criteria in Table 2.2. Seventeen articles were chosen and a further manual search was conducted on the references of these articles to identify any other articles that did not turn up on the initial MEDLINE/PubMed search. From this a further two articles were found bringing the combined total to 19 articles chosen.

Failure rate was calculated by dividing the total number of failed crowns by the total crown exposure time in years. A 95% Confidence Interval (CI) was calculated for the failure rate. A five year projection was made by multiplying the failure rate by five.

2.3.3 Results

This review shows the current published clinical studies of glass-ceramic complete crowns (leucite and lithium disilicate reinforced) report a 92% or higher survivability. There were 16 prospective studies and three retrospective studies. The total number of crowns was 2095 from cumulative data reported from all 19 studies. There were 1082 anterior teeth and 1013 posterior teeth. Three clinical studies reported a range of TOC angles (Fradeani & Aquilano, 1997; Fradeani & Redemagni, 2002; Gehrt et al., 2013) while most articles specified the margin design used except for two articles (Sjogren et al., 1999; Mansour et al., 2008) and one stated "manufacturer's instructions" (Reich et al., 2010) (Table 2.3).

2.3.3.1 Failures

Consolidating the data from all clinical studies included in this review, glass-ceramic complete crowns had an annual failure rate of 1.10% (95% CI = 1.097-1.102%). This equates to a projected 5 year failure rate of 5.49%. The annual anterior failure rate was 0.96% and posterior failure rate was 1.25%.

Removing studies with mean follow up values of less than 36 (months), the glass-ceramic complete crowns had an annual failure rate of 0.84% (95% CI = 0.75-0.93%). The revised annual failure rates were 0.71and 0.99% for anterior and posterior respectively (P = 0.30).

Common modes of failure include fracture, core fractures, break in cement, de-cementation and chipping.

Table 2.3 Clinical studies involving the survivability of glass-ceramic single crown restorations

Material	Study	Year	Survivability	Mean Follow up (months)	No of crowns	Anterior	Posterior	Period (years)	Total Occlusal Convergence	Margin design
IPS Empress	Malament et al., (2003)	2003	99.90%	60	607	358	249	10.4		Chamfer/Shoulder 1.2-1.5mm
	Sorensen et al., (1998)	1998	99.00%	36	75	47	28	3		Shoulder
	Fradeani & Aquilano, (1997)	1997	99.00%	37	144	101	43	3	5 - 10	90 degrees shoulder 1.2-1.5mm
	Fradeani & Redemagni, (2002)	2002	95.20%	78	125	93	32	11	5 - 10	90 degrees shoulder 1.2-1.5mm
	Studer et al., (1998)	1998	95.00%	61	142	67	75	2		90 degrees shoulder
	Lehner et al., (1997)	1997	95.00%	20	78	41	37	2		90 degrees shoulder 1.0-1.2mm
	Gemalmaz & Ergin, (2002)	2002	94 -95%	24.5	37	21	16	2		Shoulder 1.2 - 1.5mm
	Sjogren et al., (1999)	1999	92.00%	43.2	110	43	67	3.5		
IPS Empress II	Suputtamongkol et al., (2008)	2008	100.00%	12	30	0	30	1		Shoulder/Chamfer 1mm
	Marquardt & Strub, (2006)	2006	100.00%	60	27	0	27	5		Chamfer 1.2mm
	Taskonak & Sertgoz, (2006)	2006	100.00%	24	20	12	8	2		Shoulder 1.5mm
	Valenti & Valenti, (2009)	2009	95.50%	59	261	101	160	10		90 degrees shoulder
	Toksavul & Toman, (2007)	2007	95.00%	58	79	56	23	5		Shoulder 1-1.3mm
	Mansour et al., (2008)	2008	93.90%	25.3	82	60	22	1.5		
IPS e.max CAD	Fasbinder et al., (2010)	2010	100.00%	14	62	0	62	2		Shoulder
	Reich et al., (2010)	2010	97.40%	14	41	0	41	2		Manufacturer's instructions
	Reich & Schierz, (2012)	2012	96.30%	51	41	0	41	4.6		Shoulder/Chamfer 1mm
IPS e.max Press	Etman & Woolford, (2010)	2010	96.60%	36	30	0	30	3		Chamfer 0.8-1mm
	Gehrt et al., (2013)	2013	94.80%	79.5	104	82	22	8	6 - 15	Shoulder/Chamfer 1mm

Total occlusal convergence

Three articles reported the TOC used for the preparation of their crowns, however all three articles reported a range (Fradeani & Aquilano, 1997; Fradeani & Redemagni, 2002; Gehrt et al., 2013). These studies account for 373 crowns or 17.80% of the overall sample size. The associated failures account for 20 failures or 25% of overall failures. Sample size was considered to be too small because of the lack of information on TOC. Consequently, the relationship between TOC angle and survival could not be determined.

Margin design

Information regarding margin design was given for all except two studies. The mean failure rate per year was grouped for the different margins specified (figure 2.4). There were ten studies that specified a shoulder or a 90° shoulder design and the mean failure for this group was 1.07% per year. Two studies specified using only a chamfer design and the mean failure rate for this group was 0.56%. The remaining studies reported a shoulder/chamfer design indicating the samples in the study had margin designs of both, did not specify their margin designs, or just cited manufacturer's recommendations.

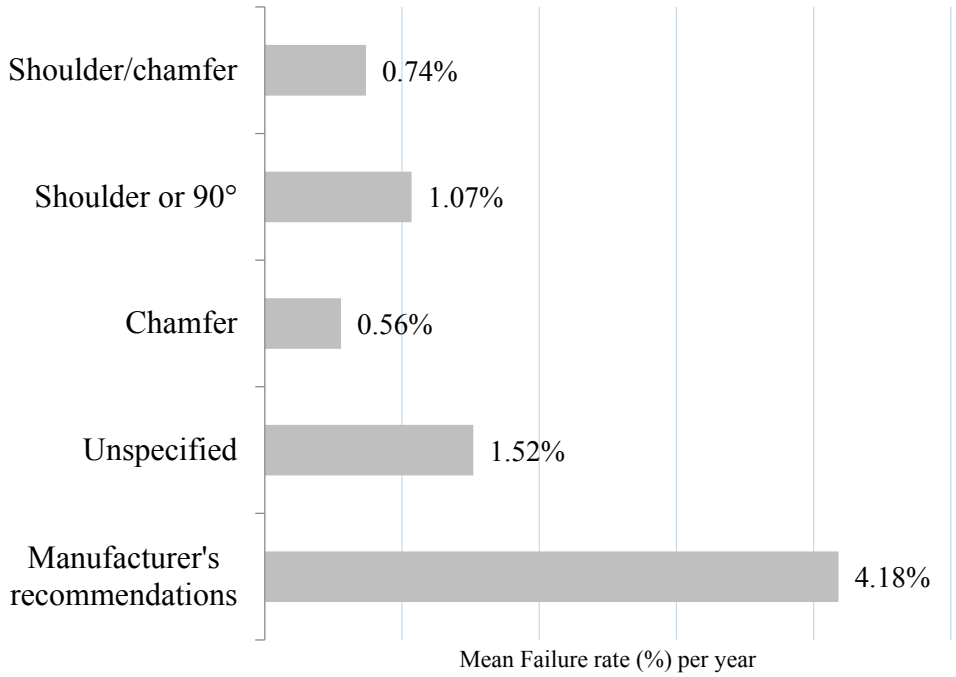


Figure 2.4 Type of margin design versus mean failure (%) rate per year

2.3.4 Discussion

In this review, a small number of short and long-term clinical studies were found in the literature, all reporting survival rates upwards of 92%, which provides a positive indication of the performance of glass-ceramics. The inclusion and exclusion criteria of this study yielded 19 clinical studies for glass-ceramic single crowns of which three were retrospective studies (Fradeani & Aquilano, 1997; Sjogren et al., 1999; Valenti & Valenti, 2009) and remainder being prospective studies. However, none were randomised controlled trials.

The observation length is an important indication providing credible information on the survivability. Only six of the studies reported results for five years or more. Many

clinical reviews reject short-term clinical studies (less than two or three years) as it could be argued that such short-term results are too short to make conclusive determinations regarding the survivability of a material. There is however, a scarcity of long-term clinical studies for glass-ceramic complete crowns. Similar reviews of all-ceramic crowns (Pjetursson et al., 2007; Wang et al., 2012) have a minimum follow-up period of at least 36 months to be included in the review. For this reason, in this review, another failure rate was calculated excluding studies with mean follow-up periods of less than 36 months.

This excluded seven of the studies and the failure rate was adjusted to 0.84%. The five-year projection for the adjusted failure rate is 4.20%.

Four studies reported 100% survivability in this revised review period (Marquardt & Strub, 2006; Taskonak & Sertgoz, 2006; Suputtamongkol et al., 2008; Fasbinder et al., 2010). However if short observation periods of less than 36 month was an exclusion criterion, three of the studies would have been excluded. Although the remaining study by (Marquardt & Strub, 2006) had a very small sample size of only 27 posterior crowns.

The two studies recording information from general practices that were not related to the authors were Sjogren et al. (1999) with 92% survivability and Mansour et al. (2008) with 93.9% survivability. They reported the lowest survivability percentages and were conducted for short periods (less than five years). Sjogren et al. (1999) reported seven fractured crowns that failed between one to four years. One crown loosened nine months after luting which was recemented and later fractured; one had a minor fracture; two had endodontic problems; and the others were unspecified but needed to be replaced. The study by (Mansour et al., 2008) was a retrospective study on general practices and did not specify the nature and exact site of each fracture. Notably, these two studies were also the same two studies that did not report margin designs. This

may be explained as the crowns were prepared by different clinicians in different general practices.

Reported failures included microleakage of cement, breakage in the resin cement, marginal chipping and occlusal and core fractures (Fradeani & Aquilano, 1997; Lehner et al., 1997; Sorensen et al., 1998; Fradeani & Redemagni, 2002; Gemalmaz & Ergin, 2002; Mansour et al., 2008; Valenti & Valenti, 2009; Reich & Schierz, 2013). Crack initiation in the luting agent due to mechanical failure is likely to initiate at the marginal area and possibly induce debonding of the restoration as it propagates (Bowley et al., 2013). Crack initiation can also occur below the occlusal surface of a posterior crown especially when the gap to be filled by the cement is substantial and resin shrinkage occurs upon curing (Kelly, 1999). Convergence angle is said to be an important factor in assisting the debonding of the restoration (Bowley et al., 2013). Furthermore, as debonding occurs in the luting agent, the flexural properties of the restoration material become a defining factor as masticatory forces are occlusally exerted (Sornsuwan and Swain, 2012). This may be an explanation for the failures initiated occlusally.

This study included leucite-reinforced and lithium disilicate glass-ceramics. Because of the limited number of studies on complete crowns in glass-ceramics, the type of material was disregarded when calculating fracture rates. Instead, the studies were pooled to give a more credible result for glass-ceramics in general. Further long-term well-designed studies are necessary in order to establish significant differences between both glass-ceramics in question.

Margin design influences the thickness and geometry of the restoration in the marginal area and can affect the glass-ceramic surface, introducing micro-cracks and flaws which is a possible explanation for marginal chipping and core fractures. In the meantime, only shoulders and chamfers were mentioned as margin designs for glass-ceramic clinical studies and bevel or knife-edge preparations were not utilised. Two articles used chamfers (Marquardt & Strub, 2006; Etman & Woolford, 2010), while

the majority used shoulders or a combination of shoulders and chamfers. Chamfers were shown to have significantly weaker strength values than shoulder preparations (Doyle et al., 1990; Friedlander et al., 1990) but this report finds the failure rate of chamfer designs almost half that of shoulder designs. Because the chamfer group only had two studies, it is too small to be conclusive. Although Bernal et al., (1993) found that when etched and bonded with resin cement, chamfers should not be significantly different than shoulders. There is a lack of information regarding the abutment height and TOC angles recorded in the studies mentioned above. Three articles reported TOC but even then, only a range of values were recorded to encompass all the preparations. Studies measuring TOC angles in non-controlled environments show that while most clinicians acknowledge the need to have a small TOC, but the recommended TOC angles are not routinely being prepared (Goodacre et al., 2001). Prothero (1923) showed that retention at 10° was only half of those at 5°. As the angle increases there is a higher chance of crown displacement when under masticatory forces. The displacement causes tensile stress in the margin and luting agent. The degree of displacement increases with increasing taper angles augmenting the chances of debonding (Bowley et al., 2013). No studies to the authors' knowledge have clinically tested the role of TOC angle with survival rates. Although discrepancies are acknowledged between recommendations and tapers produced in general practices, it may be that this discrepancy is often overlooked as literature promotes the role of the increasing strength of dental (resin) cements.

Furthermore, as many of the studies were prospective studies conducted in university settings under specialists' observations, the angle of convergence produced may not have depicted the kind of preparations produced by general practitioners in a general practice. Because the TOC plays a vital role in the retention and resistance of a crown, the resulting repercussions of significant deviations from the recommended values in clinical studies is still unknown.

The lack of information regarding the TOC and margin design in clinical studies can be attributed to the variability and complexity of measuring different parameters. There is an inherent lack of standardised methodology regarding the capturing of this information. In literature the TOC is commonly shown to be measured by projecting silhouettes of prepared dies (Ohm & Silness, 1978; Nordlander et al., 1988; Ayad et al., 2005), photocopies (Noonan & Goldfogel, 1991), photographs (Leempoel et al., 1987), or creating a digital cross sectioned image (Annerstedt et al., 1996; Oilo et al., 2003; Güth et al., 2013). Time consuming methods of measuring TOC can deter clinicians from accurately recording the TOC. This means the recording of design parameters for clinical studies is often neglected.

There is a multitude of variables that affect the survival percentages in clinical studies. The report by Anusavice (2012) highlighted the need for more specific information to be included in clinical studies regarding failures. The possibility for more information regarding the TOC and margin design could help correlate its role with the resulting etiology of failures.

The author's propose the implementation of a measuring system integrated into CAD software for data collection. This provides the potential for future clinical studies to include specific TOC and margin designs of each preparation; and also providing for future understanding of the effects of TOC and margin design on the survivability of complete crowns.

2.3.5 Conclusions

It was evident that the geometry of the initial tooth preparation plays a vital role in retention and resistance of single crown restorations. However, no clinical studies to date have focused on this topic. Although many studies report margin designs and even fewer report TOC angles, it was impossible from the information provided in these reports to ascertain their effects on the restorations clinical survivability.

Further studies need to be conducted to determine how TOC angles and margin design influences the survival rates of glass-ceramic complete crowns.

2.4 Chapter summary

Dental glass-ceramics contain crystalline structures in an amorphous glass matrix. These reinforcements improve strength whilst maintaining an aesthetically pleasing restoration. Many glass-ceramics have been developed and manufacturers continue to develop them. Glass-ceramics therefore, encompass a wide range of materials with differing mechanical properties.

Tooth preparation recommendations have not changed drastically since they were introduced as important principles in the retention and resistance of crowns. Glass-ceramics are recommended to have a 12 degree convergence angle with a 1 – 1.5 mm minimum margin width.

A review on the clinical studies of glass-ceramics showed that, although tooth preparation principles are deemed important, very few studies report the geometric parameters. The studies that did report, were vague. This suggests that clinical studies do not consider this aspect and currently there is no evidence to show tooth preparations for glass-ceramic crowns affect the clinical longevity or survivability of the restoration.

03

Clinical tooth preparations and associated measuring methods

The geometries of tooth preparations are important features that aid in the retention and resistance of cemented complete crowns. The clinically relevant values and the methods used to measure these are not clear. The purpose of this systematic review is to retrieve, organise, and critically appraise studies measuring clinical tooth preparation parameters, specifically the methodology used to measure the preparation geometry. This chapter is a published manuscript inserted in its entirety.

Janine Tiu, Basil Al-Amleh, J Neil Waddell, Warwick J Duncan. Clinical tooth preparations and associated measuring methods – a systematic review. Journal of Prosthetic Dentistry 2015: DOI: 10. 1016/j.prosdent.2014.09.007 – 1.42 Impact Factor

3.1 Introduction

The basic principles surrounding clinical longevity of indirect fixed prostheses have been extensively researched. The plethora of literature available, dating back to the early 1900s, has contributed to dedicated chapters in dental textbooks on the principles of tooth preparations (Rosenstiel et al., 2006, Shillingburg et al., 2012).

The review by Goodacre et al. (2001), considered preparation features for fixed prostheses, together with their historical basis. The primary recommendation was to maximise the retention and resistance forms of the prepared abutments to improve clinical serviceability of the restorations. Retention prevents an indirect restoration from being dislodged along the path of placement, whilst resistance prevents a restoration from being dislodged along any other axis other than the path of placement (The Glossary of Prosthodontic terms, 2005). These geometric forms predict whether the cement at the tooth-restoration interfaces in a given area is subjected to tensile, shear, or compressive forces.

The total occlusal convergence angle (TOC) has been investigated for its influence on retention and resistance (Jorgensen, 1955; Parker et al., 1988; Parker et al., 1991; Parker et al., 1993; Goodacre et al., 2001). TOC has been defined as the converging angle of two opposite axial walls in a given plane, and is generally non-material specific (The Glossary of Prosthodontic terms, 2005).

Theoretically, parallel axial walls provide maximum retention and resistance, whilst highly converging walls have the least. Jorgensen (1955) showed that as the TOC increased, the retention (g/mm) decreased in a hyperbolic relationship, with significant reduction in retention when half the TOC exceeded five degrees. Although parallel axial

walls were advocated by some early authors (Conzett, 1910), the clinical feasibility of successfully creating parallel walls without creating undercuts was impossible, thus creating the need for slight angling to allow for inconsistencies. Optimal TOC values have ranged from 2 degrees to 5.5 degrees (Prothero, 1923; Kaufman et al., 1961; el-Ebrashi et al., 1969; Gilboe et al., 1974). Clinically achievable TOC recommendations range from 6 degrees to 24 degrees and have been quoted in textbooks as being ideal (Malone et al., 1965; Dykema et al., 1986; Wilson & Chan, 1994; Rosenstiel et al., 2006; Shillingburg et al., 2012).

In the past, cross-sectional margin configurations have included feather edges (Gavelis et al., 1981) and bevels (Rosner, 1963; Hoard et al., 1976; Pardo, 1982) whereas chamfer and shoulder designs are more common today (el-Ebrashi et al., 1969; McLean et al., 1980; Gardner, 1982; Davis et al., 1983; Deane et al., 1987; Limkangwalmongkol et al., 2007). A finite element analysis showed higher stresses associated with bevel and chamfer designs compared with shoulder margins (Abu-Hassan et al., 2000). Marginal widths are material specific with minimal thicknesses described for metal crowns (0.3-0.5mm (Hunter & Hunter, 1990)), metal-ceramic (0.5 mm), and ceramic crowns (1-1.5 mm (Goodacre et al., 2001)).

The aim of this study was to systematically retrieve, organise, and critically appraise the literature on clinically achieved crown preparation parameters and the methods used to measure these parameters.

3.2 Methods and materials

The study conformed to the PRISMA study protocol (figure 3.1). A database search was performed in PubMed/Medline, ScienceDirect, and Scopus, using the search terms shown in Table 3.1. Searches in ScienceDirect were limited to the area of “Medicine and Dentistry”, “Journal Articles”, and the search terms were applied to “Abstracts, Titles, and Keywords”. Searches in Scopus were limited to the area of “Health

Sciences", and search terms were applied to "Article Title, Abstracts, Keywords and Authors".

Table 3.1. Search Strategy used for databases

Database	Date Accessed	Keywords	No. of articles
PubMed/MEDLINE	5 Dec 2013	total occlusal convergence AND crowns	27
		taper AND crown preparation	125
		angles AND crown preparation	70
		abutment height AND crown preparation	11
		margin design AND crown preparation	137
ScienceDirect	5 Dec 2013	total occlusal convergence AND crowns	10
		taper AND crown preparation	23
		angles AND crown preparation	42
		abutment height AND crown preparation	1
		margin design AND crown preparation	15
Scopus	5 Dec 2013	total occlusal convergence AND crowns	28
		taper AND crown preparation	124
		angles AND crown preparation	200
		abutment height AND crown preparation	14
		margin design AND crown preparation	179

After combining all the articles and removing duplicates, two investigators, J.T. and B.A., screened the titles and abstracts with the following inclusion and exclusion criteria:

3.2.1 Inclusion criteria

- Studies of tooth preparations carried out intra-orally or extra-orally by a clinician
- Studies measured the TOC and/or margin width and/or margin angle and/or abutment height.
- Studies clearly detailed the measuring methods

- Studies reported actual measured values
- Studies only performed on single complete crowns
- Studies published in English language journals

3.2.2 Exclusion criteria

- Studies reporting a combined buccolingual and mesiodistal average for TOC
- Reviews, case reports, letters to the editor
- Studies of onlays/inlays, fixed partial dentures, implants
- Animal studies

If the content of the study was unclear from the title and abstract (or contained no abstract) it was shortlisted, then full-text articles were read and the same criteria applied. Any disagreements between reviewers were resolved through discussions with the third author.

Data was collected by recording the following:

- Author/s of study
- Year of study
- Study performed intra-orally or extra-orally
- Number of specimens in study
- Type of tooth
- Buccolingual and mesiodistal TOC values and/or abutment height and/or margin design with standard deviations
- Operator/s or who did the crown preparations
- Method used to measure the values collected

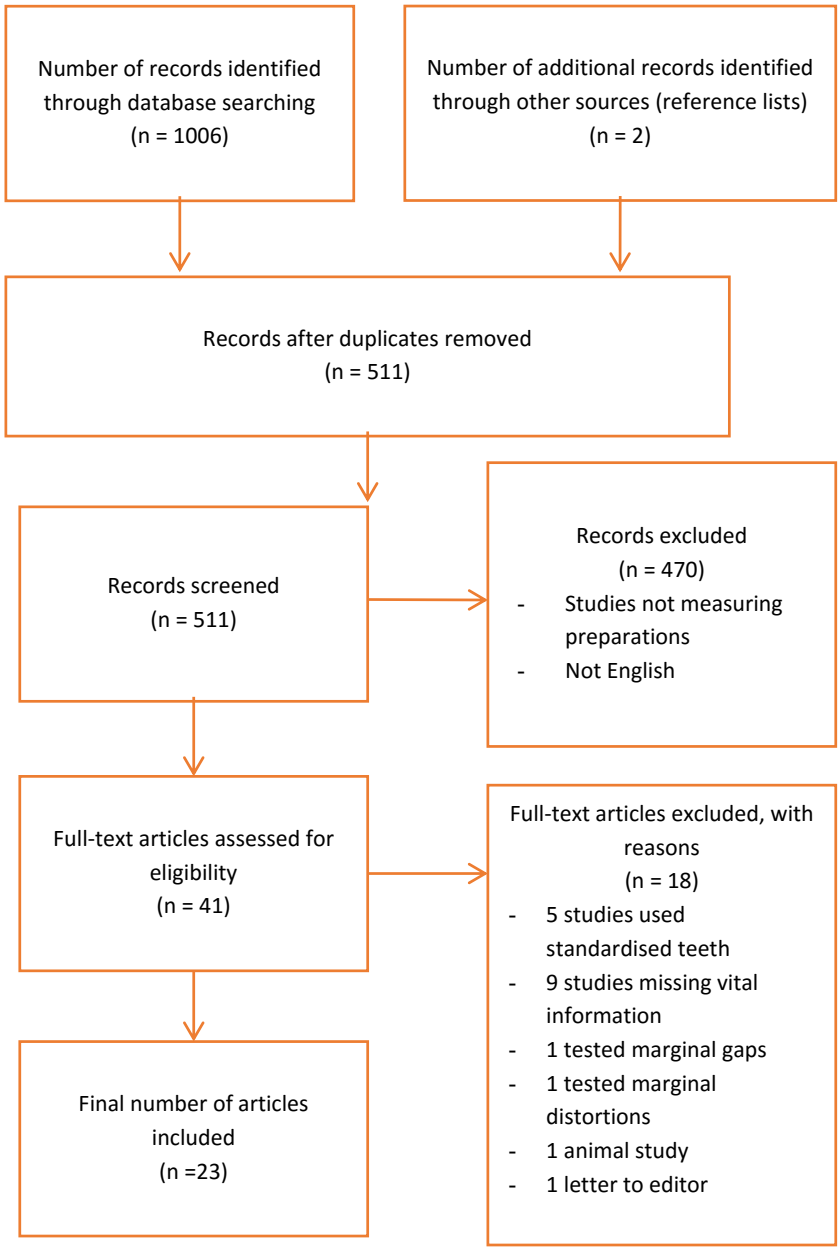


Figure 3.1 PRISMA flow diagram for identification of studies to be included in review

3.3 Results

There were 23 studies that satisfied the inclusion criteria of which 20 reported TOC angles. The studies reporting the TOC angles are chronologically summarised in Table 3.2. One study reported half the TOC angles in sufficient detail to be included (Begazo et al., 2004). In 15 studies, the crown preparations were carried out intraorally, and 5 studies had preparations performed extraorally. The mean TOC angles reported for the buccolingual dimension ranged from 7.4 degrees to 35.7 degrees, while the mean TOC angles for the mesiodistal dimension were between 7.1 degrees and 37.2 degrees.

Overall, 7295 preparations were evaluated over a period of 35 years. Approximately half (47%, n = 3446) were from the same study (Begazo et al., 2004). Of the 23 articles included in this review, 51% (n = 3713) measured TOC performed by dentists or general practitioners, 38% (n = 2758) by students, and 1% (n = 60) by clinical staff. The remaining studies failed to specify the operators, with 4% (n = 272) carried out by postgraduates and specialists, 3% (n = 236) by dentists and specialists, 2% (n = 145) by students and dentists, and 2% (n = 111) by a skilled operator.

Three studies reported the abutment heights of natural teeth (Sato et al., 1998; Etemadi et al., 1999; Guth et al., 2012). The values are tabulated in Table 3.3. One study reported the distal and mesial abutment heights (Etemadi et al., 1999), while the other two reported an average value for each abutment (Sato et al.; 1998; Guth et al., 2012). All studies were performed intra-orally and the operators included students, general dentists and prosthodontists.

The studies reporting margin width (n = 4) are presented in Table 3.4. The studies reporting margin angle (n = 4) are presented in Table 3.5. Meta-analysis was not possible for any of the reported crown preparation parameters because of the differences in the methods used to acquire the measurements.

Considerable heterogeneity was found in the measurement methods used to examine crown preparations. A classification matrix was created in this review for ease of

reporting (figure 3.2). It was found that 35% (n = 8) of the studies used manual processes to measure the silhouette of dies, 22% (n = 5) used manual processes to measure the cross section of dies, 13% (n = 3) used digital processes to measure the silhouette of dies, and 26% (n = 6) used digital processes to measure the cross section of the die.

		Process	
		Manual	**Digital**
Shape	**Silhouette**	Silhouette/Manual	Silhouette/Digital
	Cross-section	Cross-section/Manual	Cross-section/Digital

Figure 3.2 Classification matrix of measuring methods. Image shape – either an outline of a die when viewed from a certain direction (silhouette) or a cross-sectional view by means of sectioning or virtual sectioning (cross-section), and process used to measure the parameters – hand drawing lines or machines with manual processes (manual) or measured using software or computer (digital)

Table 3.2 Summary of average total occlusal convergence angles (degrees) found in literature

Study	Year	Intra-oral/ Extra-oral	n*	Tooth Type	Total Occlusal Convergence in degrees (SD)		Operators	Measuring classification
					Buccolingual	Mesiodistal		
Ohm &Silness	1978	Intra-oral	50	Mandible & maxillary incisors, cuspids, premolars	23.00 (1.01)	19.20 (0.89)	Final year students	Silhouette/Manual
Leempoel et al.	1987	Intra-oral	16	Maxillary premolars	17.50 (4.50)	14.60 (5.00)	One dentist	Silhouette/Manual
			18	Maxillary molars	21.60 (6.10)	21.40 (4.10)		
			8	Mandible premolars	14.30 (6.80)	16.70 (3.70)		
			19	Mandible molars	24.30 (8.10)	24.60 (7.00)		
			24	Maxillary premolars	17.50 (6.30)	20.40 (7.90)		
			14	Maxillary molars	20.00 (6.60)	23.40 (6.00)	One dentist	
			14	Mandible premolars	15.10 (6.20)	16.50 (4.30)		
			19	Mandible molars	31.30 (8.40)	29.20 (7.00)		
Kent et al.	1988	Intra-oral	23	Maxillary posteriors	20.70 (6.70)	16.00 (5.40)	One experienced operator	Silhouette/Manual
			88	Mandible posteriors	20.30 (7.60)	24.20 (9.90)		
Nordlander et al.	1988	Intra-oral	115	Maxillary anteriors	19.00	14.30	Dentists and specialists attempting 4 -10 degrees	Silhouette/Manual
				Maxillary premolars	14.60	16.60		
				Maxillary molars	23.40	22.40		
				Mandible anteriors	23.10	17.80		
			94	Mandible premolars	17.70	17.00		
				Mandible molars	26.60	28.00		
Long et al.	1988	Extra-oral	27	Molars	27.90 (16.40)	25.80 (10.20)	House surgeons, General dentists, specialists	Cross-section/Manual
Noonan & Goldfogel	1991	Intra-oral	775	unspecified	20.10 (9.70)	19.30 (9.90)	Students	Silhouette/Manual
			134	unspecified	15.80 (5.10)	15.50 (6.00)		
Sato et al.	1998	Intra-oral	9	Maxillary premolars	8.00 (3.30)	7.10 (4.20)	Students attempting 2-5 degrees	Silhouette/Manual
			21	Maxillary molars	12.60 (5.40)	9.40 (3.70)		
			7	Mandible premolars	7.40 (2.10)	9.20 (2.40)		
			26	Mandible molars	7.90 (4.20)	10.80 (4.30)		
Smith et al.	1999	Extra-oral	71	Maxillary posteriors	12.27 (5.20)	13.09 (6.70)	Students attempting 6 degrees	Silhouette/Manual
			56	Mandible posteriors	14.09 (7.20)	19.32 (6.70)		
			64	Mandible anteriors	14.94 (8.70)	13.17 (6.60)		

			130	Mandible posteriors	12.92 (4.90)	18.22 (7.40)	Students attempting 12 degrees	
Poon &Smales.	2001	Intra-oral	66/61	Incisors	19.45 (17.06)	12.52 (10.67)	Students and dentists	Cross-section/Manual
			12/11	Canines	22.42 (15.26)	10.55 (7.19)		
			38/39	Premolars	15.26 (8.86)	19.69 (13.00)		
			28/27	Molars	21.32 (11.51)	26.11 (12.95)		
Al-Omari &Al-Wahadni	2004	Intra-oral	29	Maxillary anteriors	19.00 (9.60)	15.60 (7.50)	Final year students attempting 10-20 degrees	Silhouette/Manual
			37	Maxillary premolars	20.80 (7.20)	17.20 (6.90)		
			27	Maxillary molars	35.70 (19.70)	28.50 (16.00)		
			17	Mandible anteriors	24.10 (7.20)	17.70 (5.10)		
			25	Mandible premolars	22.70 (12.40)	21.70 (11.30)		
			22	Mandible molars	32.50 (10.80)	37.20 (13.50)		
					Half TOC values in degrees (SD)			
Begazo et al.	2004	Intra-oral	1376	Maxillary incisors	**Buccal**	**Lingual**	**Mesial**	**Distal**	General practitioners	Cross-section/Digital
					6.6 (4.5)	9.8 (7.1)	6.0 (4.6)	6.1 (4.3)		
				Mandible incisors	5.1 (3.3)	11.1 (7.6)	5.2 (4.3)	5.2 (4.3)		
			199	Maxillary canines	7.5 (4.2)	10.9 (6.8)	7.2 (4.4)	6.4 (3.2)		
				Mandible canines	6.7 (5.3)	10.0 (9.4)	3.9 (2.2)	4.4 (2.4)		
			819	Maxillary premolars	6.0 (4.6)	7.0 (5.2)	7.4 (6.5)	7.6 (6.0)		
				Mandible premolars	7.1 (5.1)	8.0 (6.2)	7.8 (6.3)	8.2 (6.1)		
			1052	Maxillary molars	10.2 (6.2)	10.5 (7.5)	10.7 (6.5)	11.0 (6.8)		
				Mandible Molars	10.7 (7.8)	12.7 (12.3)	14.4 (10.4)	15.1 (9.8)		
Ayad et al.	2005	Extra-oral	262	Molars	17.30 (5.90)		15.20 (4.60)		1st year students	Silhouette/Manual
			200	Molars	19.80 (10.00)		19.40 (9.10)		3rd year students	
			37	Molars	15.60 (4.80)		14.10 (3.80)		4th year students	
Patel et al.	2005	Intra-oral	60	Mandible & maxillary premolars/molars	24.23 (11.23)		27.03 (15.00)		4th year students	Cross-section/Manual
			60		14.67 (5.04)		16.33 (5.82)		5th year students	
			60		14.33 (7.02)		14.88 (7.39)		GDPs	
			60		17.08 (10.39)		16.77 (6.98)		Clinical staff	
Okuyama et al.	2005	Extra-oral	46/54	Maxillary molars	34.20		20.70		Students attempting 2-5 degrees	Cross-section/Digital
Rafeek et al.	2010	Extra-oral	49	Incisors	26.70 (14.10)		14.90 (7.70)		4th year students	Cross-section/Digital
			50	Molars	18.20 (7.10)		14.20 (5.00)			
		Intra-oral	20	Incisors	31.60 (18.80)		16.80 (15.90)		5th year students	
			20	Molars	16.80 (12.30)		22.40 (12.80)			
Ghafoor et al.	2011	Intra-oral	25	Anteriors	Not reported		18.76 (6.95)		Postgrads and specialists	Silhouettes/Digital
			25	Premolars			20.24 (9.37)			

			25	Molars		29.16 (10.90)		
Ghafoor et al.	2012	Intra-oral	110	Premolars	24.32 (9.28)	20.03 (6.49)	Postgrads & specialists	Silhouettes/Digital
			87	Molars	30.44 (10.61)	29.51 (8.97)		
Alhazmi et al.	2013	Intra-oral	11	Maxillary premolars	20.80 (7.05)	16.00 (6.80)	Final year students	Cross-section/Digital
			22	Maxillary molars	24.80 (8.07)	19.80 (6.40)		
			14	Mandible premolars	23.50 (7.10)	19.60 (7.60)		
			44	Mandible molars	25.00 (8.70)	26.40 (8.20)		
Aleisa et al.	2013	Intra-oral	355	Unspecified	20.45 (11.05)	16.66 (10.07)	Students	Cross-section/Manual
Guth et al.	2013	Intra-oral	75	Maxillary molars	18.60 (8.70)	17.30 (6.20)	General dentists	Cross-section/Digital

Where n has two numbers, the first is the buccolingual value and the second is the mesiodistal value.

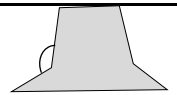
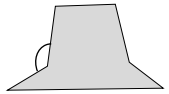
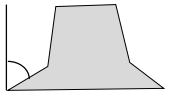
Table 3.3 Summary of average abutment heights (mm) found in literature

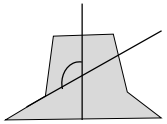
Study	Year	Intra-oral/Extra-oral	n	Tooth Type	Abutment Height in mm (SD)		Operator	Measuring method
Sato et al.	1998	Intra-oral	1	Maxillary 1st premolar	6.90 (0.00)		Students	Silhouette/Manual
			8	Maxillary 2nd premolars	6.60 (1.10)			
			11	Maxillary 1st molars	5.80 (1.20)			
			10	Maxillary 2nd molars	5.50 (1.40)			
			2	Mandible 1st premolars	6.40 (1.60)			
			5	Mandible 2nd premolars	5.80 (0.80)			
			18	Mandible 1st molars	5.70 (1.20)			
			7	Mandible 2nd molars	4.80 (0.70)			
			1	Mandible 3rd molar	5.60 (0.00)			
Etemadi et al.	1999	Intra-oral	15	Premolars	**Mesial (SD)**	**Distal (SD)**	Two Prosthodontists	Cross-section/Manual
					2.30 (0.50)	2.60 (0.50)		
				Molars	2.70 (0.80)	3.40 (0.90)		
Guth et al.	2013	Intra-oral	75	Maxillary Molars	4.10 (0.74)		General dentists	Cross-section/Digital

Table 3.4 Summary of average margin widths (mm) found in literature

Study	Year	Intra/extra oral	n	Crown type/goal thickness	Tooth Type	Margin width in mm (SD)				Operator	Measuring Method
Seymour et al.	1996	Extra-oral	4	Metal ceramic /0.8 – 1.5 mm	Maxillary right canines	0.85 (0.17)				Three Dentists	Cross section/Digital
			4		Max right 1st premolar	0.91 (0.19)					
			3		Max right 2nd premolars	0.77 (0.16)					
			2		Maxillary left canines	0.83 (0.01)					
			3		Max left 1st premolars	0.63 (0.08)					
			1		Max left 2nd premolar	0.58					
			2		Mandibular left canines	0.75 (0.02)					
			2		Man left 1st premolars	0.77 (0.18)					
			2		Man left 2nd premolars	0.50 (0.05)					
			1		Mandibular right canine	0.53					
Poon & Smales	2001	Intra-oral	68	Metal ceramic/1.0 – 1.5 mm	Incisors	0.77 (0.27)				Students and dentists	Cross-section/Manual
			10		Canines	0.91 (0.28)					
			31		Premolars	0.71 (0.28)					
			9		Molars	0.83 (0.32)					
Begazo et al.	2004	Intra-oral	1376			**Buccal(SD)**	**Lingual(SD)**	**Mesial(SD)**	**Distal (SD)**	General practitioners	Cross-section/Digital
					Maxillary incisors	0.9 (0.3)	0.9 (0.3)	0.9 (0.3)	0.9 (0.3)		
					Mandible incisors	0.7 (0.3)	0.8 (0.3)	0.6 (0.3)	0.7 (0.3)		
			199	All-ceramic/0.7-1.2 mm	Maxilla canines	0.9 (0.3)	0.9 (0.3)	0.8 (0.3)	0.9 (0.3)		
					Mandible canines	0.8 (0.3)	0.8 (0.3)	0.7 (0.3)	0.8 (0.2)		
			819		Maxillary premolars	0.9 (0.3)	0.9 (0.3)	0.8 (0.3)	0.9 (0.4)		
					Mandible premolars	0.9 (0.3)	0.8 (0.3)	0.8 (0.3)	0.8 (0.3)		
			1052		Maxillary molars	1.0 (0.3)	1.0 (0.3)	0.8 (0.3)	1.0 (0.3)		
					Mandible molars	0.9 (0.3)	1.0 (0.5)	1.0 (0.3)	0.9 (0.3)		
Al-Omari and Al-Wahadni	2004	Intra-oral	29	Metal ceramic/ shoulder (1 – 1.5 mm) chamfer (0.3 – 0.5 mm)	Maxillary anteriors	1.00 (0.29)	0.88 (0.32)	0.81 (0.24)	0.81 (0.17)	Final year students	Silhouette/Manual
			37		Maxillary premolars	0.88 (0.23)	0.78 (0.25)	0.72 (0.20)	0.62 (0.25)		
			27		Maxillary molars	0.92 (0.30)	0.74 (0.25)	0.62 (0.18)	0.57 (0.20)		
			17		Mandible anteriors	0.45 (0.09)	0.49 (0.16)	0.51 (0.28)	0.63 (0.20)		
			25		Mandible premolars	0.85 (0.22)	0.64 (0.25)	0.79 (0.23)	0.66 (0.21)		
			22		Mandible molars	0.87 (0.32)	0.80 (0.53)	0.70 (0.33)	0.61 (0.23)		

Table 3.5 Summary of average Margin Angles (degrees) found in literature

Study	Year	Intra-oral/Extra-oral	n	Tooth type	Definition of Angle/Angle goal	Margin Angle in degrees (SD)	Operator	Measuring Method
Seymour et al.	1996	Extra-oral	4	Maxillary right canines	 90 – 110 degrees	10.7.78 (12.82)	Three Dentists	Cross section/Digital
			4	Maxillary right 1st premolars		104.04 (26.51)		
			3	Maxillary right 2nd premolars		94.32 (8.28)		
			2	Maxillary left canines		108.45 (9.58)		
			3	Maxillary left 1st premolars		118.48 (14.12)		
			1	Maxillary left 2nd premolar		108.33		
			2	Mandibular left canines		100.25 (1.76)		
			2	Mandibular left 1st premolars		126.45 (12.10)		
			2	Mandibular left 2nd premolars		113.57 (3.63)		
			1	Mandibular right canine		113.5		
Poon & Smales	2001	Intra-oral	65	Incisors	 90 – 110 degrees	108.32 (13.92)	Students and dentists	Cross-section/Manual
			8	Canines		106.31 (11.31)		
			28	Premolars		101.99 (11.64)		
			9	Molars		108.17 (13.26)		
Dalvit et al	2004	Intra-oral	67	Anteriors	 Minimum 33 degrees	79.00 (14.00)	Unspecified	Silhouette/Digital
			19	Premolars		72.00 (15.00)		
			13	Molars		74.00 (14.00)		

Begazo et al.	2004	Intra-oral	1376	Maxillary incisors	 90 - 130 degrees	**Buccal (SD)**	**Lingual (SD)**	**Mesial (SD)**	**Distal(SD)**	General Practitioners	Cross-section/Digital
						120.6 (17.6)	119.5 (16.6)	115.6 (19.3)	117.0 (18.8)		
				Mandible incisors		127.4 (21.4)	125.3 (18.4)	128.0 (20.5)	129.1 (19.6)		
			199	Maxillary canines		123.6 (17.5)	122.9 (16.6)	120.5 (19.9)	119.6 (19.7)		
				Mandible canines		120.1 (21.7)	121.4 (18.4)	124.8 (16.3)	122.0 (16.2)		
			819	Maxillary premolars		123.6 (15.5)	121.3 (15.2)	119.2 (17.6)	119.7 (18.2)		
				Mandible premolars		122.8 (16.0)	123.2 (18.9)	118.9 (19.8)	117.0 (18.0)		
			1052	Maxillary molars		118.1 (14.9)	119.5 (14.9)	118.5 (17.6)	118.6 (16.1)		
				Mandible molars		118.6 (19.5)	118.3 (17.7)	113.6 (17.8)	112.8 (18.4)		

3.4 Discussion

This review presents the published evidence for geometric parameters associated with clinical crown preparation and the methods used to measure these parameters. The evidence shows a general nonconformity to the values recommended for crown preparation; considerable heterogeneity is also apparent in the measuring methods used in these studies.

Our search methodology coupled the search term "crown preparations" in all searches with geometric parameters. The limitation in this includes other search terms being synonymous with crown preparations, such as tooth preparations, dental preparations, preparations, and single-crown preparations. This initial search retrieved many articles that were not relevant to the review, including *in vitro* bench fatigue tests, strength tests, finite element analyses, and retention analysis using fixed TOC values of 32 degrees or less (Dodge et al., 1985; Zidan & Ferguson, 2003; Cameron et al., 2006; Bowley et al, 2013). Mainly relevant studies had to be excluded because they reported grouped values or ranges or did not provide enough information. Some of the included articles failed to specify anatomic location (mandible versus maxilla) (Long et al., 1988; Noonan &Goldfogel, 1991; Etemadi et al., 1999; Poon & Smales, 2001; Dalvit et al., 2004; Ayad et al., 2005; Rafeek et al., 2006; Ghafoor et al., 2011; Ghafoor et al., 2012; Aleisa et al., 2013), or type of tooth (incisor, canine, premolar, or molar)(Noonan &Goldfogel, 1991; Smith et al., 1999; Dalvit et al., 2004), and 1 article reported only a single cross-section (Ghafoor et al., 2011).

The TOC angle was the most commonly reported parameter. Several studies had mean TOC values greater than 24 degrees (Leempoel et al., 1987; Long et al., 1988; Nordlander et al., 1988; Poon & Smales, 2001; Al-Omari & Al-Wahadni, 2004; Okuyama et al., 2005; Rafeek et al., 2006; Ghafoor et al., 2011; Ghafoor et al., 2012; Alhazmi et al., 2013). The lowest range of TOC angles (7.10 to 12.60 degrees (Sato et al., 1998)), were produced intraorally by students working under the supervision of prosthodontists, who were aiming for 2 to 5 degrees (conforming to the recommended 6

to 12 degrees). This suggests that attempting very narrow angles may be the key to achieving acceptable values. However, another study with a similar experimental design (students attempting a 2- to 5- degree TOC) produced a different result, with TOC angles measuring up to 34 degrees (Okuyama et al., 2005).

Height varied considerably between studies. This is the parameter over which the clinician may have the least control because the coronal tooth structure may have previously incurred significant damage or may have received restorations of varying quality (Etemadi et al., 1999).

A general trend was noted for margin widths to fall under 1 mm. Two studies reported that the mean margin widths fell short of the desired minimum value of 0.8 to 1.5 mm (Seymour et al., 1996) or 1 to 1.5 mm (Poon & Smales, 2001). Clinicians tend to be excessively conservative, and this is likely to have both aesthetic and structural (marginal failure) repercussions when the restoration is fabricated with thin anteroposterior and buccolingual dimensions.

Kuwata (1979) classified margins based on their "margin angle," an angle defined as that formed around the surface of the margin, edge of the finish line, and a vertical projection. Chamfers were between 21 and 60 degrees whereas shoulders were classified between 61 and 90 degrees. Besides these designs, an internal 135 degree sloped or disappearing shoulder has also been presented (McLean & Wilson, 1980, Donovan et al., 1985). This internal line angle was shown to have the same effects as butt joint margins in metal/metal-ceramic restorations (McLean & Wilson, 1980). The literature has recommended a 90 degree shoulder and a 135 degree shoulder (McLean et al. 1980). The values of angles included in this study have internal values somewhere between these values.

Two studies had the same definition for margin angles and set a satisfactory range for margin angles, between 90 and 110 degrees (Seymour et al., 1996; Poon & Smales, 2001). Seymour et al (1996), concluded their values fell short of this recommendation, whereas Poon & Smales (2001), rated their preparations to be 'satisfactory' because

their values fell within this range. The definition of angle for marginal angles differed markedly among included studies. This lack of consensus on the definition alone suggests that universal standardisation is needed to better investigate the clinical consequences of the various marginal angles.

Overall, intraoral preparations were more tapered with higher TOC values than extraoral preparations, and a clear pattern was observed of increasing TOC angles moving from anterior preparations to posterior preparations. The exception was the maxillary incisors, which not only produced higher TOC angles in the buccolingual view but also always showed higher TOC values in the buccolingual view than in the mesiodistal view.

The heterogeneity in operator experience, working conditions, and ultimately the measurement methods meant no substantial comparisons could be made on the specific values. When the studies are considered chronologically, those published in the 1970s and 1980s had similar values to the more recent studies published in the 2000s, and 2010s, with the mean values remaining in a range of approximately 18- to 25- degrees. One particular study had mean TOC values reaching 37.2 degrees (Al-Omari & Al-Wahadni, 2004). An increase in the TOC angle of crown preparations may have a direct negative effect on the amount of remaining healthy tooth tissue and may therefore compromise the abutment integrity. Little mention has been made in the literature regarding the effect of the TOC on abutment structure or on other preparation parameters. In the meantime, despite advances in technology and education during the past 4 decades, we have observed little change in the analysis and reporting of TOC values.

Methods based on light projection and silhouette tracing were used in three studies (Nordlander et al., 1988; Sato et al., 1998; Smith et al., 1999). Others used projected photographic negatives (Leempoel et al., 1987; Poon & Smales, 2001), photographs (Kent et al., 1988), or photocopies of the shadow of dies (Noonan & Goldfogel, 1991). Two studies read their TOC values from microscopes (Al-Omari & Al-Wahadni, 2004; Ayad et al., 2005). Unless the projections are of a 1:1 ratio, these methods are limited to

finding values that are unaffected by size. Enlarging the die helps with identifying and calculating the resultant TOC and margin angles but cannot help with measuring height and margin width. These methods also do not account for the impact of grooves and retentive features. Another limitation with earlier studies is that a silhouette of a die is inaccurate in recording opposite sides of axial walls, as the tooth preparation geometry is asymmetric and complex.

Preparing the groundwork for future studies means measuring methodologies need to be addressed and standardised. A certain bias and subjective techniques are found with the different methods in the studies included in this review. Deducing axial walls can be subjective in terms of where exactly on the axial wall is selected for extrapolation and demarcation. Even a slight change in position can change the resultant angle by a noticeable amount, with both the left and right axial walls doubling the error.

A small number of studies attempted to address this issue by objectively evaluating the crown preparation geometry (Oilo et al., 2003; Motofumi et al., 2005). Guth et al. (2013), presented a study in which datasets were used in a similar manner to the previous studies, where 4 cross sections were used to calculate the TOC value. This study also attempted to set up rules for quantifying the other preparation parameters. However, we consider that the criteria used to delineate the area and calculate the TOC were still vague and subject to different interpretations. Hey et al. (2013), presented analytical software for quantifying the marginal area with a view to future clinical use' although TOC was not recorded, the margin width was defined as the distance to the axial wall 1 mm above the preparation margin. Recently, a new method has been suggested and validated for objectively measuring crown preparations. The method relies on a mathematical formula to objectively select specific points to measure the geometry (Tiu et al., 2014). Standardising the method would improve coherence and enable valid comparisons of future studies.

Although several studies have acknowledged that ideal TOC angles are rarely achieved, it would be interesting to see if ideal values are ever consistently achieved. Sato et al. (2008) mentioned that the ideal goal of a 2- to 5- degree standard should not be changed

but acknowledged that a 10-degree TOC was more clinically achievable, whereas Smith et al. (1999) considered a 6-degree TOC criterion to be unrealistic.

Emphasis has been placed on education and trying to train preclinical students to create ideal preparations. Many of the studies measured student-performed preparations. In one experiment, experienced prosthodontists supervised every step of the process (Sato et al. 2008). Another conducted the study with students using typodonts on bench tops and also on a simulation model (Smith et al., 1999). The TOC values from these studies fell short of the recommended values. More recently, digital assistance software has been produced to train students (Jager et al., 2003; Kournetas et al., 2004; Esser et al. 2006; Cardoso et al., 2006). A study used real-time magnification for teaching students and found an improvement in performance (Robinson et al., 2001). These have been useful in enhancing the learning process of crown preparations for students, but to the authors' knowledge, no studies have suggested that the preparations performed with these systems have significantly improved the quality of preparations in practice.

Perhaps the focus should shift from trying to educate the train students to an unrealistic standard. Although proper training should be given, it may be time to respond to the studies and opinions and revise the current recommendations. If a disparity already exists between recommendations and clinical values. Then what are the consequences and where does the threshold lie before a noticeable failure occurs? These questions will remain unanswered unless clinical trials accurately report preparation parameters for each crown instead of just reporting a range (Fradeani et al., 1997; Fradeani et al, 2002).

Each tooth in the dental arch has a uniquely complex geometry (size and shape) specific to its function, and teeth vary not only intra-arch and inter-arch but also between persons. The idea that tooth preparation principles with finite values can be applied to all situations in a one-size-fits-all approach belies what is clinically achievable and creates a disparity between recommendations put forth in the literature or by manufacturers and the reality of general practice. Considering that exact specific angles cannot be consistently achieved, clinical recommendations ought to be tooth specific and provide an acceptable range. The methodologies used for measuring values such as

TOC and margin geometry on complex dental geometric shapes in the clinical setting are the main problem with these historical numerical recommendations. Currently, no universally accepted standards exist for measuring these key features in crown preparations; as a result, a large amount of bias exists in the literature. Moreover, the vast majority of studies that have dictated these preparation principles are based on *in vitro* studies and not on sound clinical trials. Raising the issue of evidence-based clinical practice. However, a reliance on low-level evidence is not surprising, given the difficulty involved in measuring TOC and margin geometry in clinical trials.

3.5 Conclusions

Within the last few decades, recommendations have increased from 2 to 5 degrees to account for clinical achievability. The TOC seems to be the most important preparation parameter as more studies are available on this parameter than on abutment height, margin width, and margin angle. More studies were also conducted intraorally than extraorally, but preparations performed extraorally had values closer to those recommended than those performed intraorally. Also, more studies reported values measured from silhouettes, which do not truly represent opposing axial walls. Future studies should be based on cross sections of crown preparations. Standardised measurement and reporting are needed for future studies that analyse preparation geometry in a simple and objective fashion. Clinical trials are needed to determine the implications of values that exceed those recommended by the literature and the combined effect of all the preparation parameters.

04

Development of the coordinate geometry method

A validated universal method requiring no human input is needed to capture and evaluate preparation geometries in a manner that can be used to see the correlation of different parameters. The purpose of this study is to present a method of capturing and evaluating crown preparation geometry. This chapter is a published manuscript inserted in its entirety.

Janine Tiu, J Neil Waddell, Basil Al-Amleh, Wendy-Ann Jansen van Vuuren, Michael V Swain. Coordinate geometry method for capturing and evaluating crown preparation geometry. Journal of Prosthetic Dentistry 2013: DOI: 10. 1016/j.prosdent.2013.11.012 – 1.42 Impact Factor

4.1 Introduction

The process of measuring preparation geometry such as the total occlusal convergence (TOC) angle and occlusocervical (OC) dimension of complete crowns has evolved in the dental literature (Ohm & Silness, 1987; Leempoel et al., 1987; Kent et al., 1988; Norlander et al., 1988; Noonan & Goldfogel, 1991; Annerstedt et al., 1996; Seymour et al., 1996; Poon & Smales, 2001; Ayad et al., 2005). First, a distinction must be made between crowns fabricated for *in vitro* testing and those provided to patients. Test specimens are fabricated to exact specifications by using parallel milling devices and tapered grinding instruments with a known angle (Woolsey & Matich, 1978; Potts et al., 1980; Dodge et al., 1985; Wiskott et al., 1996; Wiskott et al., 1997). A parent mold is usually created to ensure all specimens adhere to the same specific measurements and geometry. By machining synthetic plastic on a turning tool to make testing specimens, Jorgensen (1955), was able to ascertain the relationship between retention and TOC in complete crowns.

In reality, preparations are performed chair side and *in vivo*. The systematic review in the previous chapter identified previous methods used in the past to measure the crown preparation geometry. A common technique to measure the TOC angle is to use a light projection to project the silhouette of a prepared die then to trace the outline (Ohm & Silness, 1978; Norlander et al., 1988; Ayad et al., 2005). Similar studies have captured the die by making photocopies (Noonan & Goldfogel, 1991), or photographs (Leempoel et al., 1987). Once the image has been captured. Convergent lines are drawn and protractors are used to determine the TOC. However, these image-capturing techniques for measuring TOC did not compensate for the asymmetrical shape of the preparation. Annerstedt et al (1996) presented a study by where the outline of the die was obtained

by cross-sectioned views generated by computer-aided design (CAD) software. These images were used to manually determine the convergent angles. Oilo et al (2003) also used information in CAD software but used a set of mathematical algorithms to determine the TOC. Guth et al. (2013) also used CAD software to analyse sterolithography (STL) files and instead of measuring two planes (buccolingual and mesiodistal), increased the accuracy by measuring four planes. The methods for measuring described in this study required human input to maintain consistency in testing.

The OC dimension measurement is an important parameter because it increases the retentive area and displacement resistance (Woolsey & Matich, 1978; Maxwell et al., 1990). This dimension has been measured using micrometers and rulers (Leong et al., 2009). Often these measurements are given in millimeters with one significant figure. Inconsistency occurs with this parameter as different OC dimensions are seen on a prepared die depending on where the dimension is measured.

Margins dictate the effect of the distribution of occlusal forces exerted on the restoration on the underlying tissue (Friedlander et al., 1990). With many failures observed or attributed to the marginal area, margin configurations are said to be the weakest link of the system. There is currently no standard of measuring or evaluating margins. Although a commonly visually inspected parameter (Guth et al., 2013), any observed errors are difficult to quantify. Because of this, the extent in terms of survivability is almost impossible to calculate.

Larger prepared abutments are known to have a larger surface area and therefore greater retention. Retention is defined as the ability to oppose the removal of the restoration along its path of insertion, while resistance is the ability to oppose the removal of the restoration along any path that is not its path of insertion (The Glossary of Prosthodontics Terms, 2005). Die preparations are asymmetrical, and calculating surface area is impossible without proper CAD technology. Calculating retention from surface area has largely been omitted when it comes to measuring and comparing. Because retention and resistance are related and cannot exist without each other,

resistance form is regarded as an essential component in determining the success of complete crowns (Woolsey & Matich, 1978; Potts et al., 2004).

Two theories on resistance form are described in the literature. Parker et al. (1988; 1993) published several articles on a limiting taper concept. The resistance form of a crown was either "on" or "off," and an exact quantitative limit was calculated on the basis of a base/height ratio. In contrast, Wiskott et al. (1996) determined that the relationship between convergence angles and resistance form was linear.

Although new materials that aid the retention and resistance of complete crowns appear in the dental community from time to time, the designs of the preparations have remained relatively unchanged. It is generally accepted that minimum convergence angles should be produced with an ideal OC dimension according to the tooth and situation. The greatest change has been the transition from bevels and feather edges to more shoulder/chamfer-like margins, with beveled shoulders no longer being taught or recommended (Goodacre et al., 2001). The most recent restorative materials and resin cement luting agents have proved notably strong in the oral environment (Blatz et al., 2003), and because of this, accurate preparation geometries may be perceived as negligible. What is not fully explained in the dental literature is the complex system of preparation geometry: TOC angle, OC dimension, margin design, surface area, and their combined effects on the retention and resistance on complete crowns.

Simple parameters have been tested to find optimum values, but many of these exceed recommendations even though the restoration is still shown to function competently. The complex system of retention and resistance is multifactorial and cannot be attributed solely to single parameters (Kaufman et al., 1961; Rekow et al., 2011). The need exists for a validated universal method requiring no human input to capture and evaluate preparation geometries in a manner that can be used to see the correlation of different parameters. The purpose of this study is to present a theoretical method of capturing and evaluating crown preparation geometry.

4.2 Material and methods

A 2-dimensional schematic representation of a complete crown preparation will have finish line points, margin areas, axial walls, and an occlusal surface. By allocating coordinates to these points simple geometric calculations such as the TOC, OC dimension, margin width, and base width can be achieved (figure 4.1).

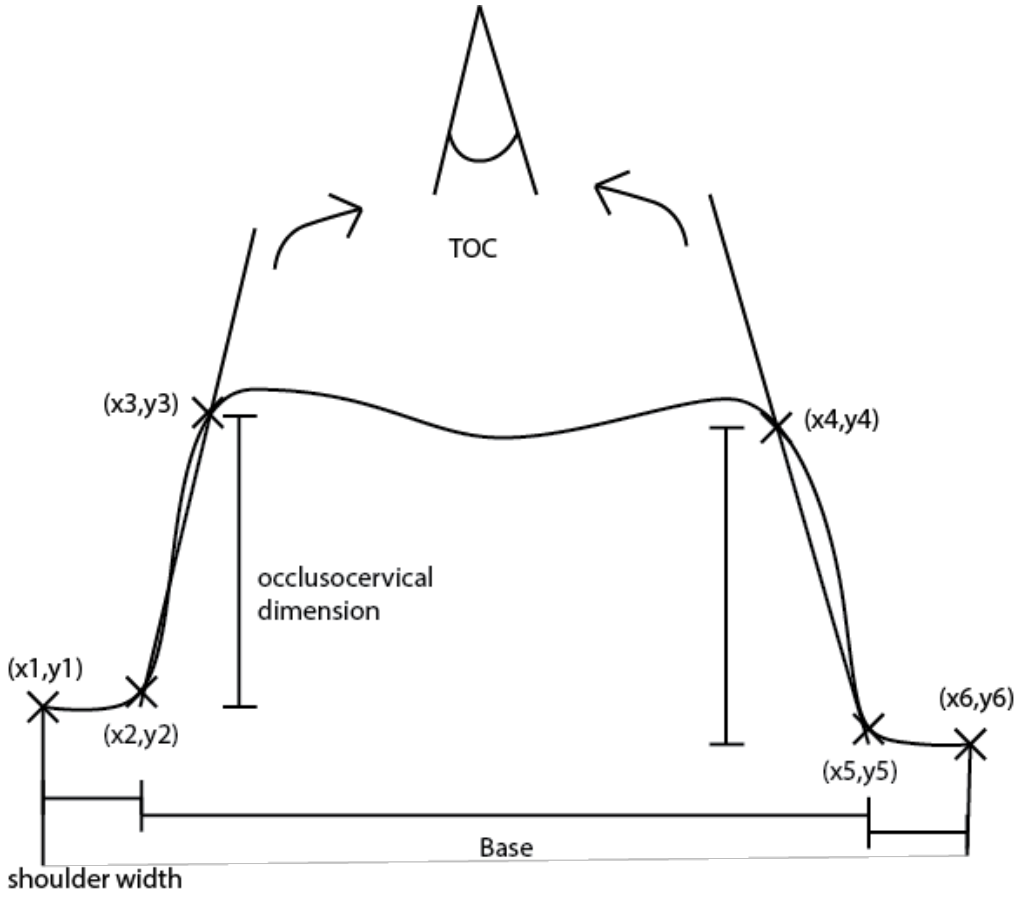
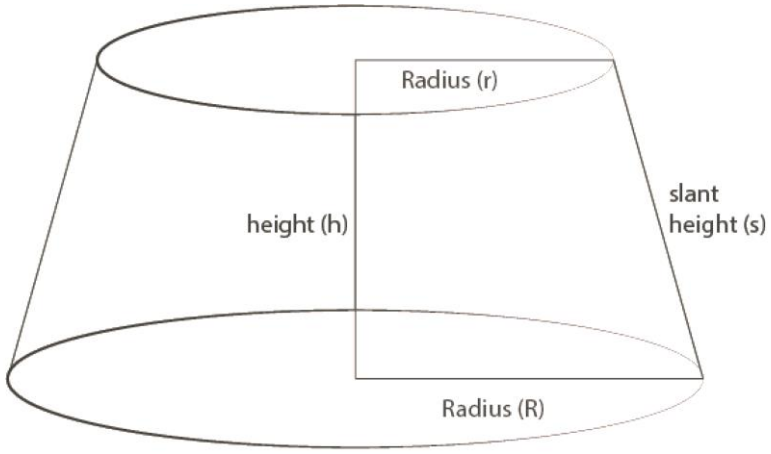


Figure 4.1 Schematic drawing of cross-sectioned preparation. Coordinates correspond to specific points, and with these coordinates, TOC occlusocervical dimension, shoulder width, and base can be calculated. TOC, total occlusal convergence.

In attempts to calculate surface area, the preparation shape is simplified into a truncated cone shape. With average values from the buccolingual and mesiodistal views, an approximate value can be achieved. Given that different teeth have limited sizes and therefore surface areas (that is, molars being bigger than incisors), a comparative value would be achieved by calculating the surface area/volume ratio (SA/V). By using the same coordinates in figure 4.1, an approximate ratio can be calculated (figure 4.2).



$$s = \sqrt{h^2 + (R - r)^2}$$

$$Surface\ Area\ (SA) = \pi[s(R + r) + R^2 + r^2]$$

$$Volume\ (V) = \frac{1}{3}\pi h(R^2 + r^2 + R.r)$$

Figure 4.2 Truncated cone with equations to calculate surface area and volume

4.2.1 Resistance value

This study did not aim to show preference to the differing theories of resistance form. The advantage of using coordinates to determine specific points means that both the limiting taper calculations and a value of resistance form can be calculated.

The limiting taper theory is based on the method described by Parker et al. (1988; 1993) and refers to figure 4.3.

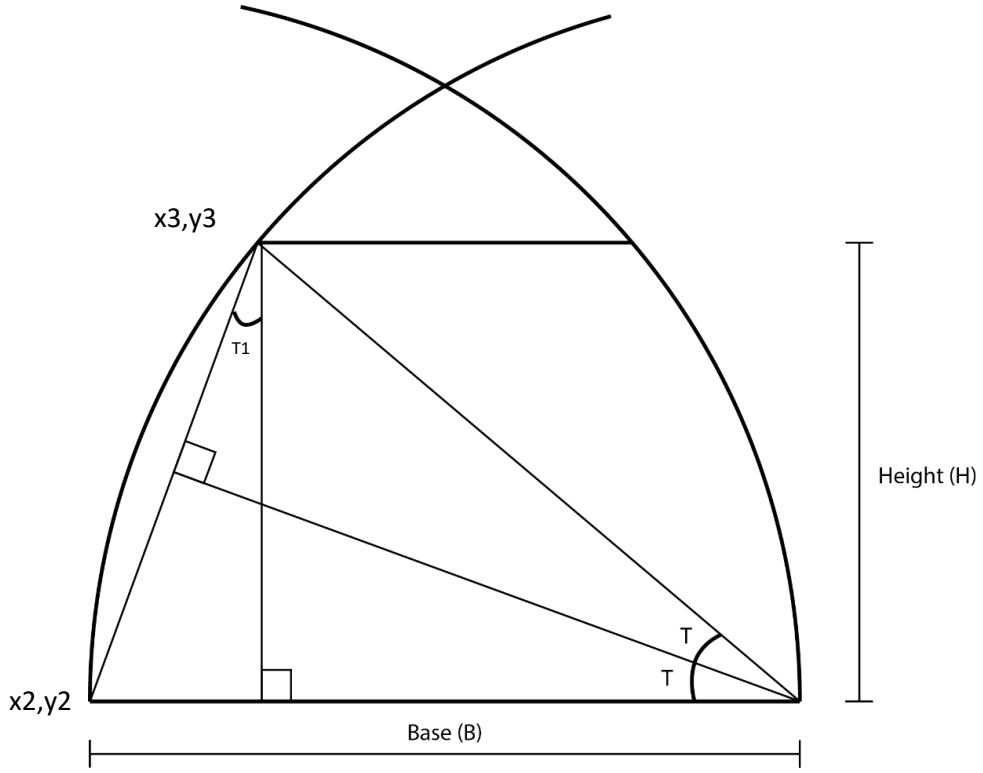


Figure 4.3 Limiting Taper adapted from Parker et al (1988; 1993)

If H is the occlusocervical dimension, B is the base of preparation, and T1 is the average taper (taper between x2, y2, and x3, y3), then the limiting taper is

$T(H/B) = ½ \sin^{-1} (H/B)$

If T1 is greater than this value, then the resistance form is “off” and the preparation does not have resistance form. If T1 is less than this value, then the resistance form is “on” and the preparation has resistance form.

The resistance length equation was shown in the study by Leong et al (2009). A resistance length formula is presented that is based on an area on the axial wall that interferes with the rotation of the crown. When a crown is rotated, an area inside the crown compresses part of the axial wall, and this area in compression is the basis for the following formula:

$N = 2(B-W) \times \sin\theta$

$RL = (H/\cos\theta) - N$

Where N is the nonresistive length of the axial wall, B is the buccopalatal width, W is the width of shoulder preparation, H is the preparation height, θ is T1, and RL is resistance length.

If RL values are >0, then the preparation has resistance form, and if RL values are <0, the preparation has no resistance form.

4.2.2 Application

One manually milled acrylic resin block (12 degree TOC bur, Milling Device Af350; Amann Girrbach) was prepared for validation of the accuracy of the method.

Nine preparations for ceramic complete crowns (monolithic lithium disilicate crowns) were prepared by general dentists. The distribution of the types of preparations is shown in Table 4.1.

The preparations were scanned (Nobel Biocare 3D scanner; Nobel Biocare), and buccolingual and mesiodistal cross-section images were collected. The images were

imported into digitizing software (Engauge Digitizer 4.1; Free Software Foundation) to convert the outlines into x and y coordinates. The 6 points were chosen by using a set of algorithms, and resulting parameters were calculated.

Table 4.1 Distribution of prepared tooth types used

Tooth Type	Dental Laboratories	
	Mandibular	Maxillary
Incisor	1	1
Canine	-	1
Premolar	1	1
Molar	2	2

The criteria for selecting the 6 points are outlined in Table 4.2. A pilot study determined that 15 degrees of angular difference produced more consistent points and reliable differentiation between the preparation transition changes from the margin to the axial wall.

Table 4.2 Criteria for determining 6 points used to calculate parameters

Point	Criteria
x1,y1	Largest angular difference around finish line area
x2,y2	Angular difference over 15 degrees cervical of most linear part of axial wall
x3,y3	Angular difference over 15 degrees occlusal of most linear part of axial wall
x4,y4	Angular difference over 15 degrees occlusal of most linear part of axial wall
x5,y5	Angular difference over 15 degrees cervical of most linear part of axial wall
x6,y6	Largest angular difference around finish line area

4.3 Results

4.3.1 Validation using the milled acrylic resin block

An acrylic resin block abutment was milled with a 12 degree TOC bur and was milled to have a shoulder width greater than 1 mm. The results of the calculations are shown in Table 4.3. The bur was also scanned and measured by using the same method. The TOC for the bur was 11.24 degrees. This means the average ½ TOC of the bur was 5.62 degrees. The milled acrylic resin block had an average half TOV value of 5.675 degrees; therefore, the error was found to be 0.05 degrees.

Table 4.3 Results from milled acrylic resin block

	Shoulder width 1	**Shoulder width 2**	**TOC**
Milled acrylic resin block	1.21 mm	1.29 mm	11.35 degrees

4.3.2 Ceramic crown preparations

Table 4.4 provides the TOC values for each view of each tooth, the average TOC of the whole preparation, average OC dimensions, average margin width, and average base dimension. Mean and standard deviations are also provided for each parameter. Average TOC values ranged from 18 degrees to 52 degrees. The mean average margin width was 0.70 mm. and the mean average base dimension was 6.23 mm.

The surface area and volumes are shown in Table 4.5. The mandibular incisor had the highest SA/V ratio value, and mandibular molar 1 had the lowest SA/V ratio value.

Table 4.4 Specimens with TOC in buccolingual and mesiodistal cross sections, average TOC of whole preparation, average OC dimension, average margin width, and average base dimension

Tooth	View	TOC (degrees)	Average TOC (degrees)	Average OC dimension (h)	Average margin width	Average base dimension
Maxillary Incisor	BL	48.23	51.84	4.60 mm	1.12 mm	4.73 mm
	MD	55.45		3.60 mm	0.92 mm	6.22 mm
Mandibular Incisor	BL	25.94	23.21	3.56 mm	0.79 mm	4.20 mm
	MD	20.49		2.38 mm	0.47 mm	2.94 mm
Maxillary Canine	BL	27.73	29.54	4.51 mm	0.34 mm	6.56 mm
	MD	31.34		3.04 mm	0.93 mm	3.87 mm
Maxillary Premolar	BL	19.16	18.07	3.38 mm	0.18 mm	7.18 mm
	MD	16.97		2.23 mm	0.12 mm	4.32 mm
Mandibular Premolar	BL	26.91	27.15	4.61 mm	0.23 mm	7.01 mm
	MD	27.39		2.21 mm	1.06 mm	3.60 mm
Maxillary Molar 1	BL	57.02	45.98	2.11 mm	0.59 mm	9.84 mm
	MD	34.93		1.81 mm	0.57 mm	7.73 mm
Maxillary Molar 2	BL	32.16	33.49	2.35 mm	0.82 mm	7.35 mm
	MD	34.81		2.57 mm	0.71 mm	5.55 mm
Mandibular Molar 1	BL	27.26	33.37	2.13 mm	1.42 mm	7.05 mm
	MD	39.47		2.60 mm	0.74 mm	8.83 mm
Mandibular Molar 2	BL	28.81	31.59	2.60 mm	0.66 mm	7.81 mm
	MD	34.37		1.89 mm	0.99 mm	7.27 mm
Mean		32.69	32.69	2.90 mm	0.70 mm	6.23 mm
SD		11.29	10.54	0.93	0.35	1.92

Table 4.5 Table showing tooth, average occlusocervical dimension, average occlusal radius, average cervical radius, average slant height, surface area, volume, and surface area/volume ratio.

Tooth	Average OC dimension (h)	Average occlusal radius (r)	Average cervical radius (R)	Average slant height (s)	Surface area (SA)	Volume (V)	SA/V ratio
Maxillary Incisor	4.10 mm	0.76 mm	2.74 mm	4.57 mm	75.55 mm	43.56 mm	1.73
Mandibular Incisor	2.97 mm	1.19 mm	1.79 mm	3.04 mm	42.86 mm	20.92 mm	2.05
Maxillary Canine	3.77 mm	1.55 mm	2.61 mm	3.93 mm	80.21 mm	52.29 mm	1.53
Maxillary Premolar	2.80 mm	2.27 mm	2.88 mm	2.92 mm	89.39 mm	58.58 mm	1.53
Mandibular Premolar	3.40 mm	1.57 mm	2.65 mm	3.62 mm	77.94 mm	48.81 mm	1.60
Maxillary Molar 1	1.96 mm	3.52 mm	4.39 mm	2.15 mm	153.16 mm	96.81 mm	1.58
Maxillary Molar 2	2.46 mm	2.45 mm	3.23 mm	2.60 mm	97.96 mm	62.78 mm	1.56
Mandibular Molar 1	2.37 mm	3.21 mm	3.97 mm	2.50 mm	138.26 mm	96.13 mm	1.44
Mandibular Molar 2	2.25 mm	3.13 mm	3.77 mm	2.35 mm	126.37 mm	84.32 mm	1.50
Mean	2.90 mm	2.18 mm	3.11 mm	3.08 mm	97.97 mm	62.69 mm	1.61
SD	0.73	0.98	0.81	0.81	35.01	25.44	0.18

4.3.3 Resistance form

Figure 4.4 shows the resistance form by using the mean resistance length (RL) value. The maxillary molar 1, mandibular incisor, mandibular molar 1, and maxillary molar 2 demonstrate resistance form, while the rest of the specimens do not. Figure 4.5 shows the limiting taper concept being calculated for the 9 specimens; only the mandibular incisor was found to have a resistance form.

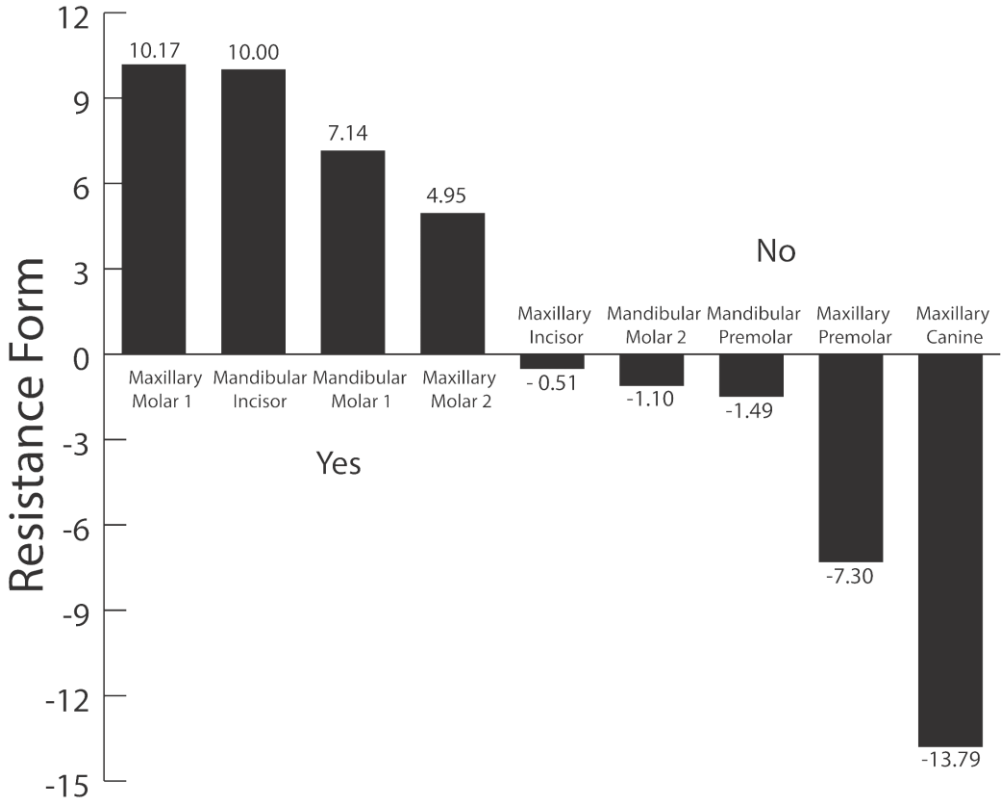


Figure 4.4 Resistance length value arranged from highest value to lowest value with values > 0 having resistance form and <0 having no resistance form.

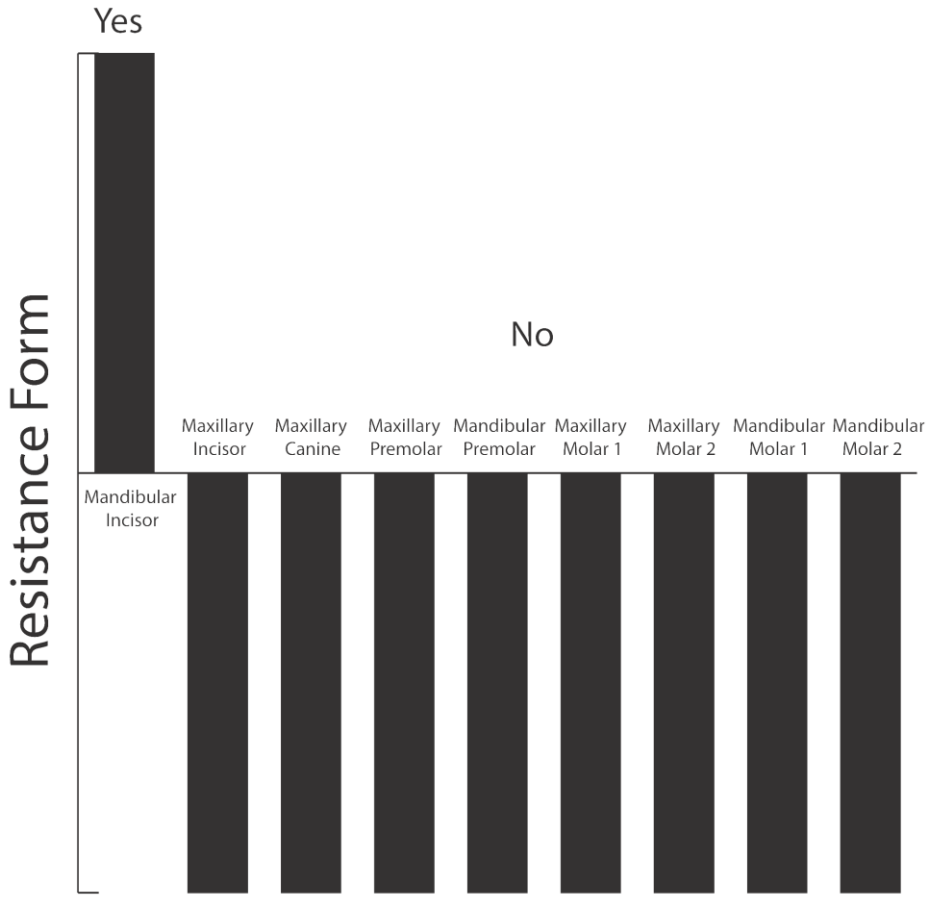


Figure 4.5 Limiting taper from preparations demonstrating a high resistance form to lowest resistance form, with values below zero demonstrating no resistance form.

4.4 Discussion

The results from the milled acrylic resin block correlated to the known information about its parameters. The shoulder widths were greater than 1 mm, but the exact measurements were not known before being scanned and therefore cannot be validated. A 6-degree bur was used to mill the axial walls, which equates to a 12 degree TOC. The values of T1 and T2 are different because of the tilt the model may have been at while being scanned, which is why the TOC value is valid. The milled acrylic resin abutment had an average ½ TOC of 5.62 degrees (TOC = 11.24 degrees). This indicates the error was only 0.05 degrees, showing the accuracy of the method.

By examining solely, the TOC values, only the maxillary premolar had a TOC that fell within the recommended 10 to 20 degrees. Although promising, the same preparation demonstrated poor margin widths, with the second poorest SA/V ratio. The maxillary premolar also had no resistance form according to both the resistance length value and the limiting taper theory. The mandibular incisor had an acceptable TOC value of 23.21 degrees and average margin widths of 0.79 mm and 0.47 mm. However, it demonstrated the highest SA/V value and was the only preparation to demonstrate resistance form in both the RL value and limiting taper theory.

The current manufacturer guidelines (Ivoclar Vivadent, Liechtenstein) suggest a TOC of 12 degrees with a minimum shoulder width of 1 mm. None of the preparations had TOC values close to 12 degrees, and all the average shoulder widths were below 1 mm. This shows that although some preparations do not adhere to the recommended values, the combination of other parameters may provide enough compensation for a clinically adequate preparation.

Alternative methods for quantifying margin designs were not reported in this study. Preparations can have many different margin configurations on the facial, proximal, and lingual surfaces. If the classification were a chamfer, shoulder, feather edge, or groove, then these would be easily identified. By taking a cross section of a margin, the method

in this study has the advantage of quantifying the margin for further tests to understand its strength consequences.

The method also measures several parameters so that the multifactorial issues can be addressed. With further analysis, patterns can be observed, with possible relationships depicted in a mathematical formula. This study required human input for manual conversion to digitizing software, for aiding in the selection of the 6 points, and for all the calculations. With further development, all these processes can be fully automated to produce a completely objective method of evaluation.

When used to calculate the retention potential, the SA/V ratio produced values inconsistent with the resistance length. A more relevant value would be obtained by calculating the surface area without including the base and occlusal surface. This is a simple modification of the truncated cone formula. The dimensions used to calculate the surface area and volume are mere approximations, and the values produced are only useful for comparing preparations. Also, this study used 2 cross-sectional planes of a 3-dimensional preparation, but the method described can measure as many cross-sectional planes as needed to obtain more accurate values.

The problem with determining if and how preparation parameters affect the retention and resistance of a clinical restoration over several years is that quantifying geometric parameters is difficult and current methods still require human input, increasing the risk of error.

By using a mathematical modeling approach to capture and evaluate processes, a more accurate, objective, and uniform method is used. The criteria for defining parameters and selecting associated coordinates negate the need for human input and subjectivity. This study combines multidisciplinary methodology from computer sciences and dentistry in a small but growing field of dental informatics. The processes produced in this methodology can be maximized by producing software capable of complex analysis either for research data or educational purposes. Further studies are needed regarding the strength consequences of the combined parameters.

4.5 Conclusion

The method described provides a foundation for accurately evaluating preparation geometry without human input.

05

Development of software for measuring crown preparations

This chapter introduces the software Preppr™, developed from the theoretical foundations in the previous chapter. It covers the software description and covers the mathematical background in its development, as well as validation and case studies. This chapter is currently being prepared as a manuscript for publication.

5.1 Introduction

Tooth preparation principles continue as a fundamental educational focus in fixed prosthodontics. Every day, clinicians employ these principles to maximise the retention and resistance and in turn, the longevity of the resulting crowns. Differences in tooth structure intra-arch, inter-arch, and between individuals, combined with the many controllable parameters that comprise the geometry results in a tooth preparation with a factorial amount of combinations.

Measuring the controllable parameters of a tooth preparation is not a new idea. In 1978, Ohm and Silness (1978) measured tooth preparations by projecting the dies onto a larger screen, the silhouette was then traced and the axial walls were extrapolated to determine the converging angle. Since then, a number of studies have used the same or similar methods (Leempoel et al, 1987; Kent et al, 1988; Nordlander et al, 1988; Noonan & Goldfogel, 1991; Sato et al, 1998; Smith et al, 1999; Al-Omari & Al-Wahadni, 2004; Ayad et al, 2005). More recently, advancements in CAD/CAM technology has shown to support the methods for measuring preparation geometry with many studies using stereolithography (.STL) file formats from their CAD software (Annerstedt et al, 1996; Begazo et al, 2004; Okuyama et al, 2005; Rafeek et al, 2006; Guth et al, 2012; Alhazmi et al, 2013). These digital methods have not only decreased the workload needed to measure the preparations, but the ability to measure a cross-section instead of a silhouette has led to more accurate converging angles.

Digital methods provide the current standard when obtaining an image of a preparation. The problem lies with the measuring aspect. One study (Annerstedt et al, 1996) was able to obtain a cross-section image of a die by digital means, but the images were printed and the converging angles were obtained by protractors. Some studies used

software to extract the preparation geometry but unless the research group was the same, no two studies have used the same software (Begazo et al, 2004; Okuyama et al, 2005; Rafeek et al, 2006; Ghafoor et al, 2011; Ghafoor et al, 2012; Alhazmi et al, 2013).

The variability in measuring the preparation parameters reported in the literature has caused all the methods subjective in application. For instance, to determine the most important parameter – the total occlusal convergence angle (TOC) of the prepared tooth, the most common method is to select two points at the cervical and at the occlusal portion of an axial wall. Lines are drawn and the converging angle measured. The selections of the points are made subjectively by 1 or more investigators and therefore always open to dispute.

The previous chapter highlighted the need for an objective selection processes and introduced a rule for selecting points. Applying a rule for selecting points substantially decreases the cognitive bias existing within and between studies.

Preparation geometry parameters are of interest to practitioners, researchers, and industry personnel. Humans and animals have teeth which are essential tools to bite and chew. With each tooth in each individual being unique, the information we can acquire on tooth geometry and forms is boundless. We are in the age of big data, where vast amounts of information can shape our understanding and future. In restorative dentistry, the preparation geometry is dictated by the existing structures and the type of restorative material used. But do practitioners adhere to the recommendations set out by manufacturers? If preparation geometry does not follow the current recommendations, how long is the restoration likely to survive? Can manufacturers design materials to suit practitioners' preference for preparation geometry? And do the public have grounds to complain if practitioners do not follow preparation recommendations despite the fact that they may in fact not be clinically relevant? The questions laid out are examples of how such information can impact our understanding of teeth.

This chapter introduces analytical software for measuring and collecting tooth preparation parameters – Preppr™. Preppr™ is the computer program created based on

our previous methodological theory. It is an easy-to-use analytical tool to measure tooth preparation parameters. This chapter describes the features of the program, validates the values by scanning milling burs of known convergence angles and comparing the output numbers. The mathematical background is presented as well as an example of a clinical analysis performed with the software tool.

5.2 Software description

Preppr™ is designed primarily for researchers and academics to collect data for clinical research, students and teachers to evaluate their tooth preparations for educational purposes, and general dentists to evaluate their preparations for retention and resistance. For the purposes of data collection, Preppr™ is paired with a custom spread sheet (Microsoft Excel, Redmond, Washington: Microsoft, 2007, Computer Software) complete with an Excel Visual Basic for Applications (VBA) User Form and preplaced formulas needed to calculate the parameters.

5.3 System requirements

The software is written in the programming language Java and can run on any computer with the ability to run Java applications (or freely available at java.com). The software accepts stereolithography (STL) files, a standard file format used in 3D scanning and printing (figure 5.1). The file is easily attainable from open systems or can be unlocked from the manufacturer. The files used in this study were taken from the 3D scanner at the Faculty of Dentistry, University of Otago (Ceramill Map400, AmannGirrbach, accuracy 20 μm).

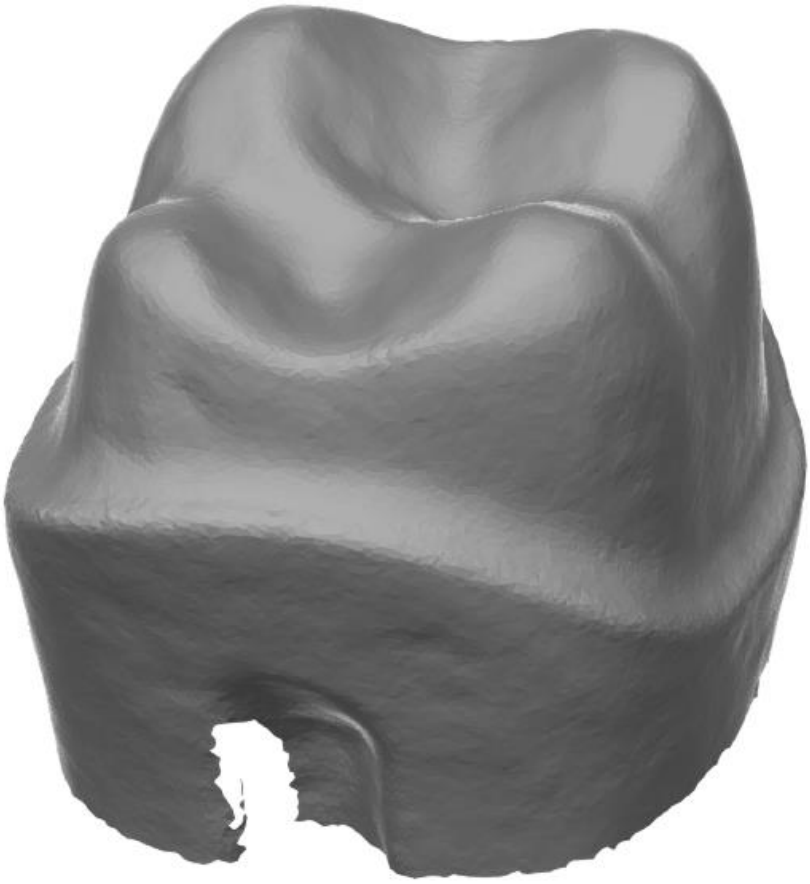


Figure 5.1 STL image of maxillary molar

5.4 The user interface

There is a single window in Preppr™ as seen in figure 5.2. This includes all the viewing frames and buttons needed to measure crown preparations. After uploading the file and going through the analysis. The display windows are seen as in figure 5.3.

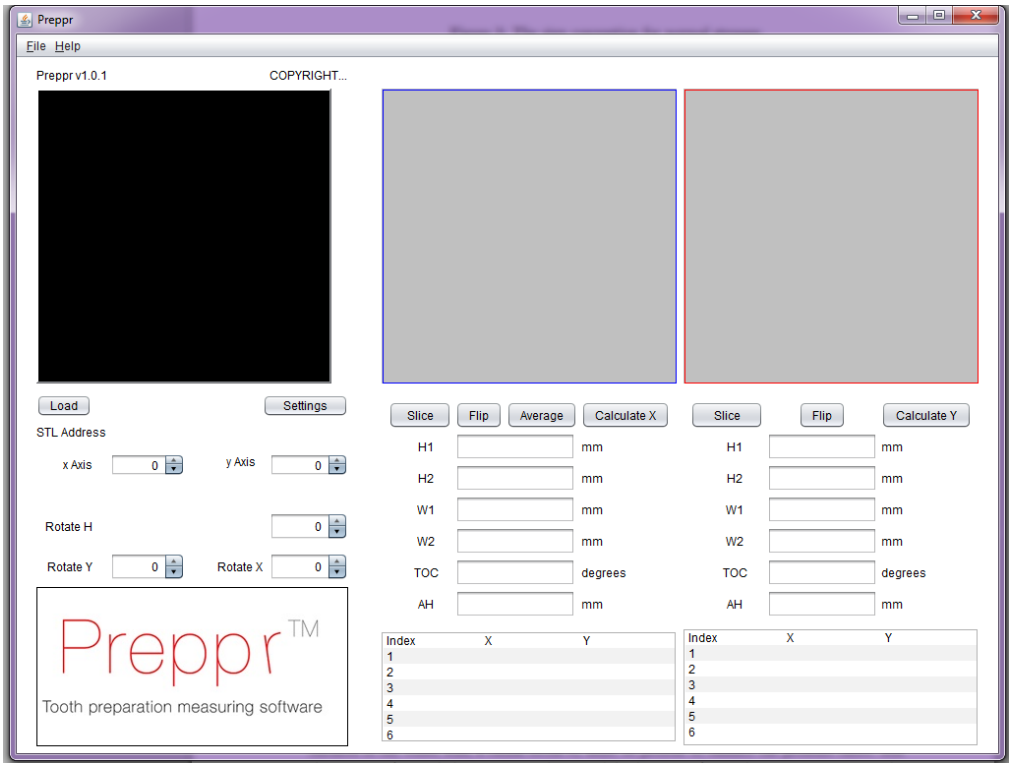


Figure 5.2 User interface

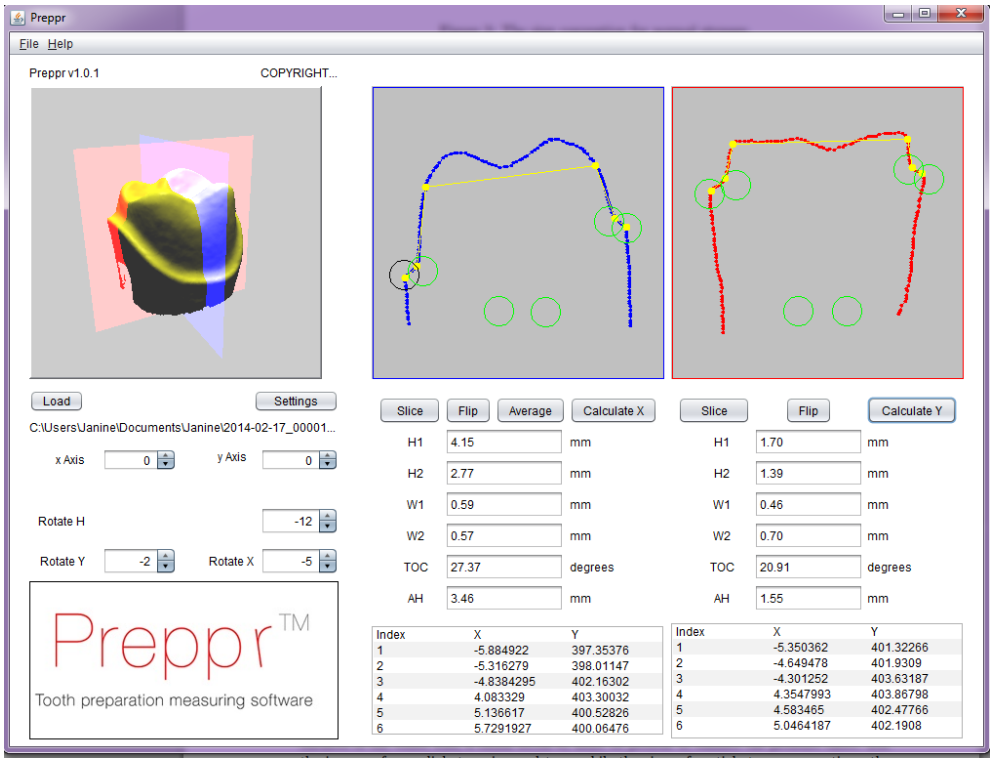


Figure 5.3 User interface after measuring

5.5 Workflow

This section presents the Preppr™ workflow using a generic maxillary molar preparation (tooth 16) for an all-ceramic restoration (figure 5.1).

1. The .STL file of the scanned preparation is extracted and is loaded into Preppr™.
2. The model is rotated to get the two bisecting perpendicular planes into the correct position (figure 5.4).
3. The x and y planes are manipulated (y plane moves in x axis; x plane moves in y axis) to find the correct position.

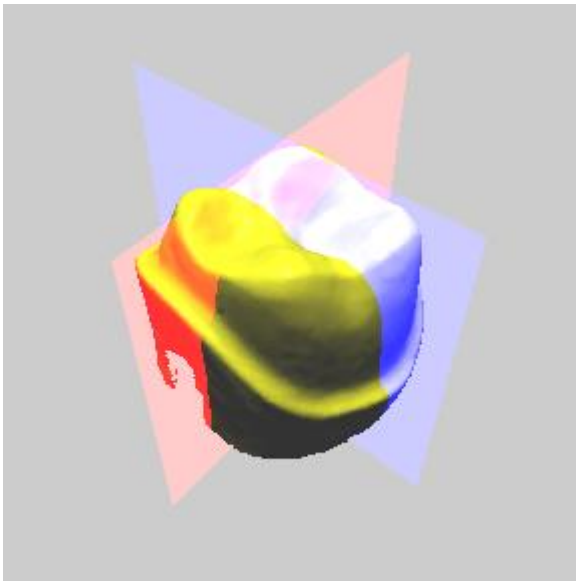


Figure 5.4 Faciolingual and mesiodistal planes showing translation and rotation

4. The 'slice' button is selected to automate the outlines of the faciolingual (FL) and mesiodistal (MD) cross sections
5. The 'analyse' button is selected to access six circles which the user drags the desired areas (the two finish lines, the cervical portions of the axial walls and the occlusal portions of the axial walls) (figure 5.5).

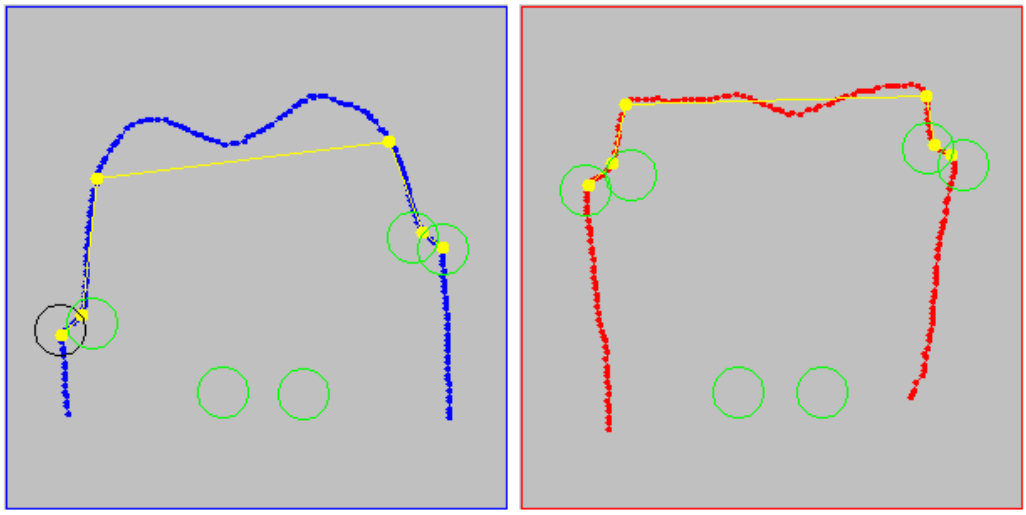


Figure 5.5 Cross-sectioned views with isolating green circles to assist the objective selection of specific point to be used.

6. The ‘calculate’ button is selected to bring up the six coordinates and the TOC angles.
7. The coordinates are copied onto the user form in the accompanying customised excel spreadsheet which outputs all the values (figure 5.6).

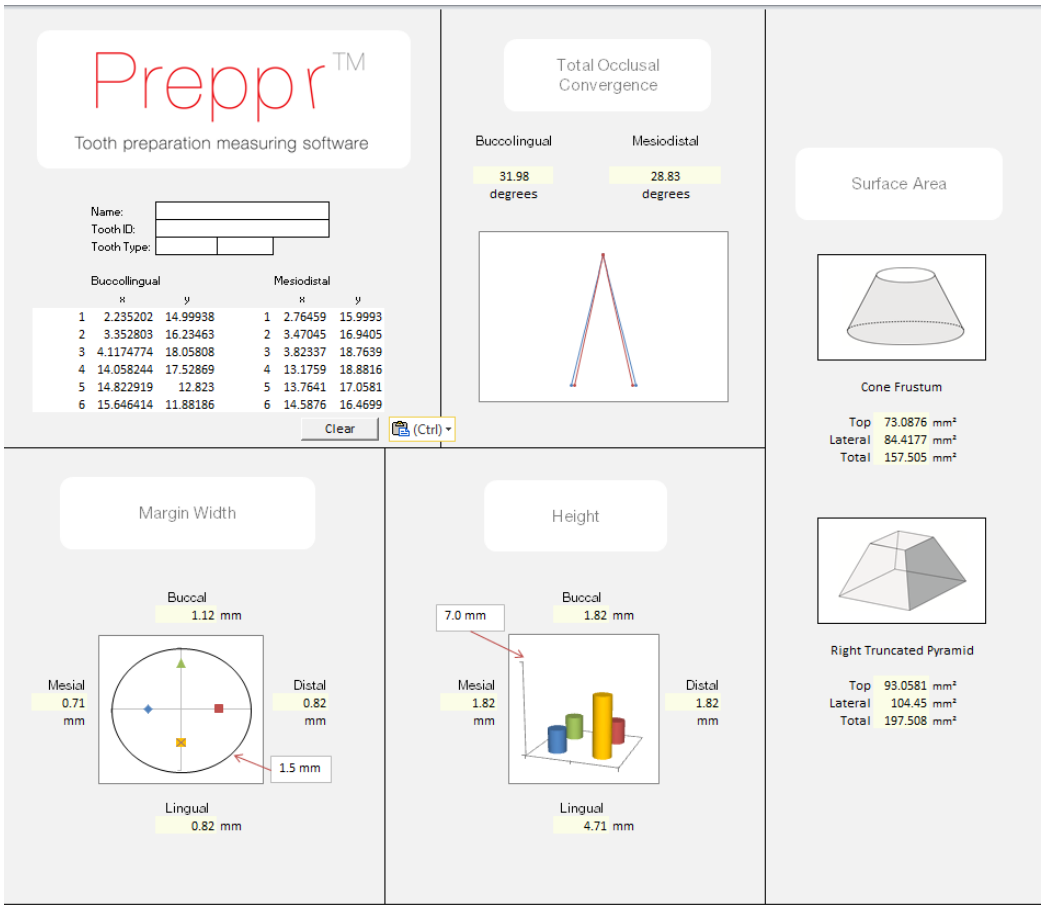


Figure 5.6 Screen capture of Preppr™ report in Excel worksheet showing output of total occlusal convergence, margin width, and height.

The variety of cross-sectional shapes of the dies required an isolation of a specific area to select the required points. For this reason, the solution was to introduce isolating circles coloured 'green' in the program. Although they require manual placement, a governing equation lies within the circles to objectively select the point.

After entering coordinates into the accompanied Excel spreadsheet, the report is shown in figure 5.6. The all-ceramic preparation had a TOC at the FL and MD aspect of 31.98 degrees and 28.83 degrees respectively. Of interest is the margin width in this preparation, where the facial width satisfied the recommended 1 mm minimal thickness while the other margins fell short. Being a maxillary molar preparation, it is no surprise

that the abutment height was the largest at the palatal aspect. Of concern however are the short heights achieved at the facial(F), mesial(M) and distal(D) axial walls of this preparation that may affect the overall retention and resistance form of this abutment. Finally, the approximated surface area of the preparation according to the cone frustum and the right truncated pyramid equations were 158 and 198 mm^2 respectively. Simplified workflow process is shown in figure 5.7.

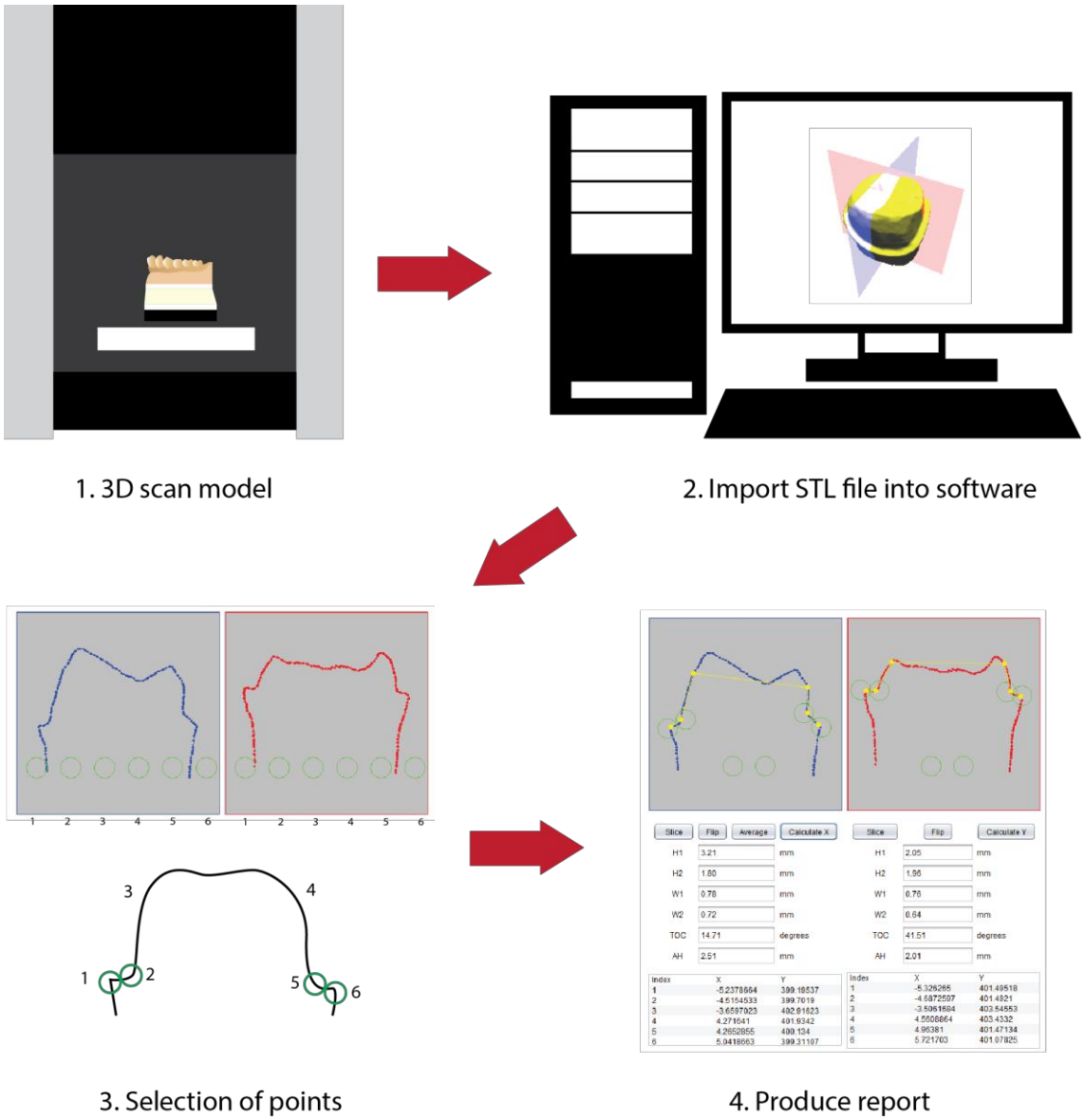


Figure 5.7 Simplified workflow process

5.6 Mathematical background

The mathematical background was based on the theory described in the previous chapter. As the software was being developed, it became apparent that the mathematical background needed to evolve to isolate the areas of interest. This saw the introduction of isolating circles and the use of the Bezier Polynomial.

The unique feature of Preppr™ is the mathematics governing the point selecting circles, making the method more objective than other available software. This section will look at the underlying mathematics after the user has placed the circles (figure 5.8).

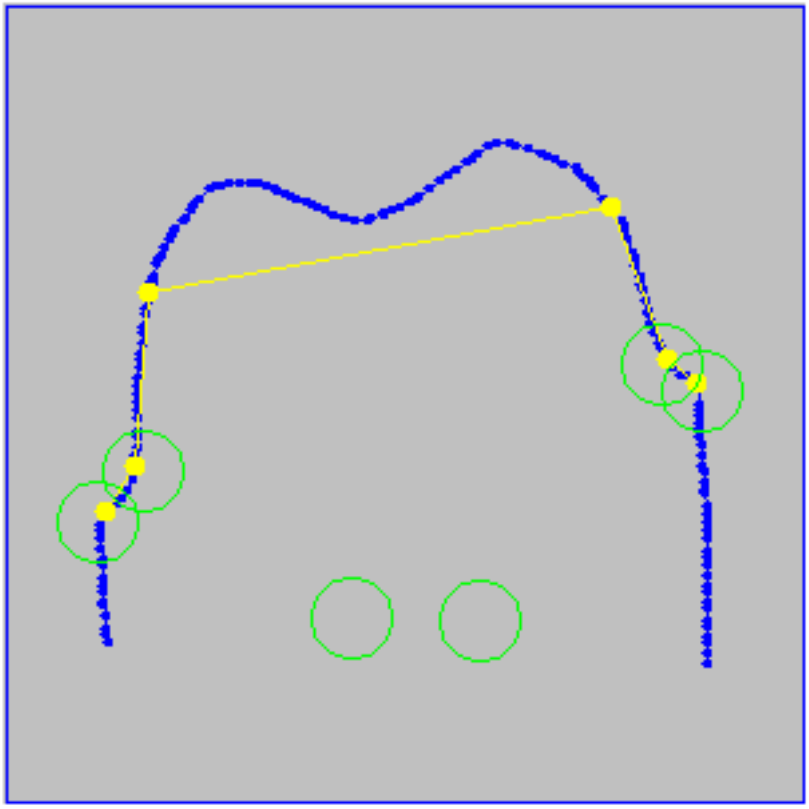


Figure 5.8 Screenshot from software Preppr™ after preparation has been sliced at cross section and after user has placed circles

Beginning from the point closest to the centre, the user places a circle containing at least 7 points. As this moves, it keeps a moving average of the angle.

When the moving average of the angle does not differ by more than 5 degrees and more than 7 points have been passed, the program locks on and effectively counts this locked on point and the origin point as a straight line. The moving average of the angle is recorded at this point

The program then continues along the line, until the difference between the moving average and the recorded moving average differs by more than 5 degrees.

Using the Bezier polynomial equation (see next subsection), the exact point on the curve when the deviation occurs is able to be isolated. This then becomes the point for the secondary circle. The same steps are repeated on the other side of the tooth and a line is drawn between them.

5.6.1 Bezier polynomial

After placement of the first circle, the program isolates each point and creates a list of the angles between each point.

When determining the angle between the points, linear interpolation doesn't give an accurate enough result, since it doesn't account for the existing gradient. To solve this problem, interpolating a Bezier cubic was used (Bezier, 1970). This looks at 4 points to determine the curve between the middle two points. Once the curve equation is determined, any point and gradient within the curve can be calculated.

The theory behind the curve is as follows:

The cubic Bezier function $\mathbf{B}(t)$, given by:

Equation 1 Bezier Cubic Polynomial

$$B(t) = (1-t)^3 P_0 + 3(1-t)^2\, tP_1 + 3(1-t)^2\, t^2 P_2 + \, t^3 P_3, 0 \le t \le 1$$

Where $P_{0\text{-}3}$ are the 4 points

Differentiating, the slope of the curve is:

Equation 2 Bezier cubic polynomial gradient

$$B'^{(t)} = 3(1-t)^2(P_1 - P_0) + 6(1-t)t(P_2 - P_1) + 3t)^2\, (P_3 - P_2)$$

One of the characteristics of a Bezier curve is that while the curve starts at P_0 and ends at P_3, the curve does not necessarily pass through P_1 or P_2. In order to determine the point at which the curve actually passes through, *t=1/3* and *t=2/3* needs to be substituted into **B**(*t*) to get the new points B_1 *and* B_2.

$$B_1 = 3P_1 - \frac{3}{2}P_2 - \frac{5}{6}P_0 + \frac{1}{3}P_3$$

$$B_2 = -\frac{3}{2}P_1 + 3P_2 - \frac{1}{3}P_0 + \frac{5}{6}P_3$$

These four points (P_0, B_1, B_2, P_3) represent the points that the curve *must* pass through and correspond to our points on the tooth.

To find the gradient given a point

The slope in Equation 2 is expressed as a quadratic equation, where P_0, B_1, B_2, P_3 are all known. To determine the slope **B**'(*t*) at any point in the curve *t*, P_0, B_1, B_2, P_3, t is substituted into the equation.

If *t* is unknown, the increment along the curve from 0 < t < 1 in 0.1 increments and apply the least square error to find the *t* value that gives the point on the curve closest to the given point

Finding a point given a gradient

Equation 2 can be rearranged into the generic quadratic equation:

$$At^2 + Bt + C = 0$$

Where:

$$A = -P_0 + 3B_1 - 3B_2 + P_3$$

$$B = 2P_0 - 4B_1 + 2B_2$$

$$C = -P_0 + B_1$$

To find a given gradient m = (**F**'(y) / **F**'(x))

First find **F'**(y) given as $\mathbf{B_y}$'(t) and **F'**(x) given as $\mathbf{B_x}$'(t). Therefore, m = $\mathbf{B_y}$'(t)/ $\mathbf{B_x}$'(t). This is also shown as:

$$\mathbf{B}'(\mathrm{t}) = \frac{\mathbf{B}'(\mathrm{y})}{\mathbf{B}'(\mathrm{x})}$$

or, for a given gradient and to find t, it is rearranged as:

$$\mathbf{B}'(\mathrm{y}) - \mathbf{gradient} * \mathbf{B}'(\mathrm{x}) = 0$$

Then solve **B**'(t) for any desired gradient to find the point on the curve with the desired gradient

5.7 Validation

Three milling burs of angle sizes parallel, 2 degrees, and 6 degrees (Komet, Germany) were scanned and the files were uploaded into Preppr™. An image of each milling bur was also uploaded into Photoshop CS5 (Adobe Systems) and the TOC for each bur was measured by the conventional method of subjective point selection and were compared to the TOC output from the Preppr™ software.

The results are shown in figure 5.9 where the values for software and Photoshop for the parallel milling bur is 0 degrees. TOC for the 2-degree milling bur was 4.18 degrees for Photoshop and 4.10 degrees for Preppr™, and TOC for the 6-degree milling bur was 12.24 degrees for Photoshop and 11.73 degrees for Preppr™. The difference is insignificant but also show that the milling burs may have a slight variation in them during production.

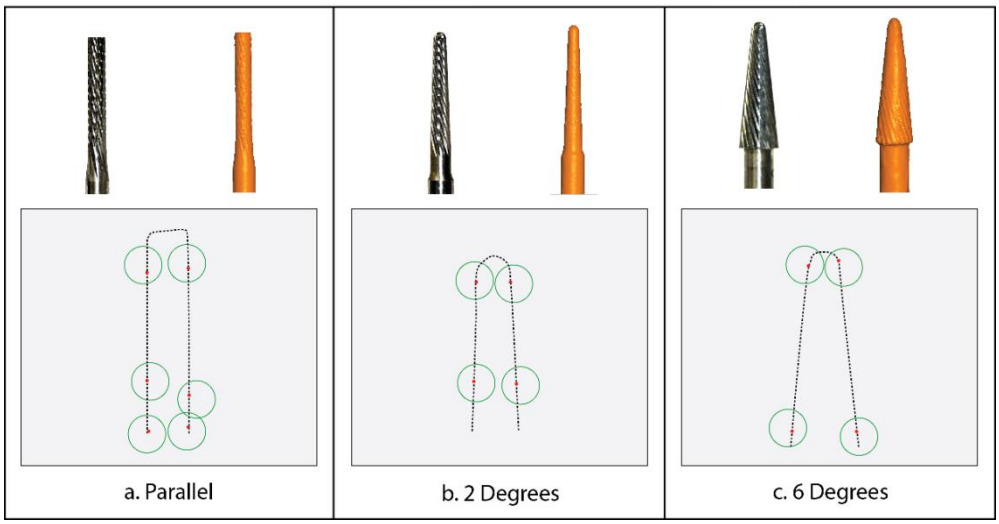


Figure 5.9 Photo, 3D scan, and Preppr™ output of the 3 milling burs – a. Parallel milling bur, b. 2 degrees milling bur, c. 6 degrees milling bur.

5.8 Case Study

The maxillary arch of the subject in this study required a single gold crown on the upper right first molar and a porcelain-fused-to-metal 3-unit bridge with the abutments on the upper right canine and second premolar. An experienced clinician prepared the teeth. The preparations are shown in figure 5.10.



Figure 5.10 Intraoral photos showing crown and 3-unit bridge preparations.

The single gold crown preparation was scanned and the Preppr™ report is shown in figure 5.11.

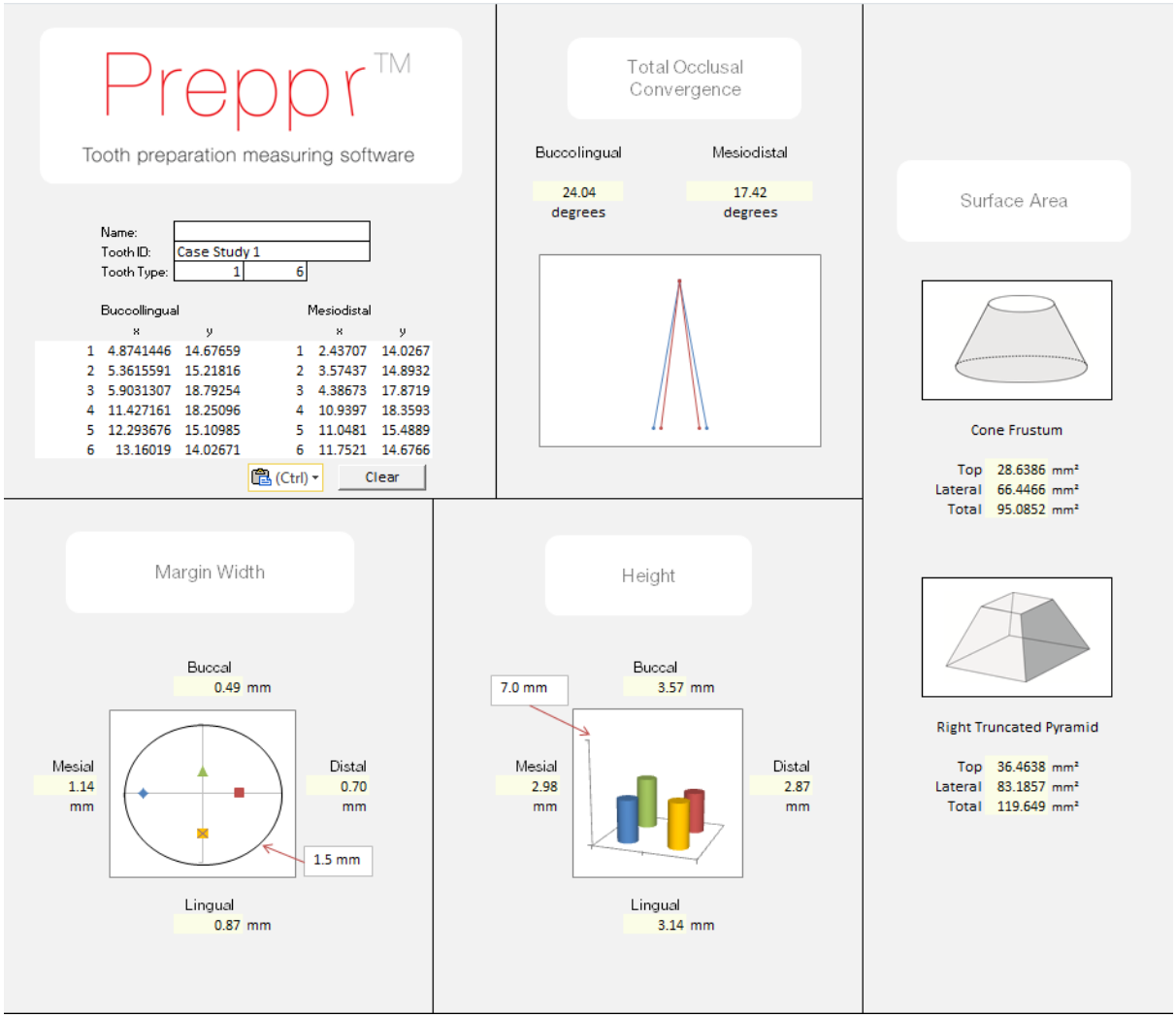


Figure 5.11 Screen capture of Preppr™ report in Excel worksheet showing output of total occlusal convergence, margin width, and height for single gold crown.

Preppr™ has the ability to measure the TOC angle from the two abutment preparations of a bridge (figure 5.12). The mesial side of the mesial abutment was 19.18 degrees, the distal side of the distal abutment was 11.43 degrees, and the TOC angle of bridge was 30.61 degrees.

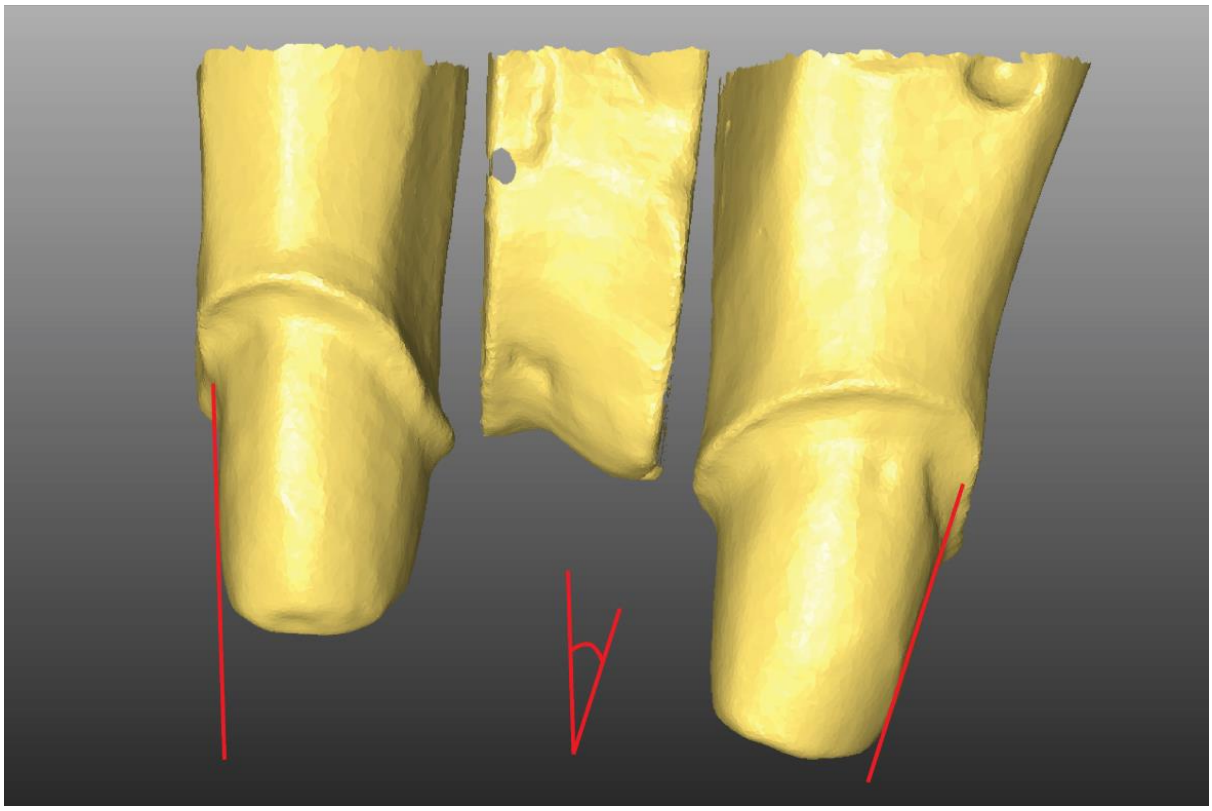


Figure 5.12 Total occlusal convergence angle of bridge preparation

5.9 Future of Preppr™

Preppr™ is continuously being refined and upgraded. Currently, Preppr™ is being used in ongoing studies to measure clinician and student's preparations for feedback and educational purposes. It is expected in this digital era to see the move away from traditional methods of measuring abutment geometries using subjective testing methods such as taking photographs and methods which have undefined or subjective means of measuring the TOC to an objective digitally driven process. It is expected that this software can be expanded in the future to encompass many more variables.

5.10 Conclusions

There is still a considerable interest in measuring tooth preparations in fixed prosthodontics. The literature is focused mainly on the education side but the current tools available for such analysis are impractical. Previous methods have been described in the literature, however we believe that until now none of them have combined the following features:

- Capability to upload .STL files straight from 3D scanning software.
- Ability to measure buccolingual and mesiodistal cross-sections.
- Ability to objectively select the points needed for TOC measurement.
- Ability to calculate all the important geometric parameters.
- Creation of reports and the capability to export, and perform large-scale analysis.

Preppr™ is a useful tool for researchers and clinicians who wish to measure the tooth preparation parameters without searching for general STL slicing software. Useful information is being produced in a timelier fashion and a larger dataset is easily measured.

06

Measuring clinical crowns (1/2)

The purpose of this study was to compare clinical achieved tooth preparations for ceramic crowns by general dentists with the recommended values found in the literature using an objective measuring method. This chapter is a published manuscript inserted in its entirety.

Janine Tiu, Basil Al-Amleh, J Neil Waddell, Warwick J Duncan. Reporting numeric values of complete crowns. Part 1: Clinical preparation parameters. Journal of Prosthetic Dentistry 2015: DOI:10.1016/j.prosdent.2015.01.006. – 1.42 Impact Factor

6.1 Introduction

Patients routinely receive complete crowns as a fixed prosthodontic treatment. Common practice requires that tooth preparation principles be used before crown placement to promote the retention and resistance of the restoration. But do clinicians routinely create ideal crown preparations? The answer is uncertain. Even if clinicians are willing to measure their work, an implemented system for objectively measuring crown preparations does not exist.

Available today are clinical recommendations derived from the early works of Prothero (1923), and Jorgensen (1955). The total occlusal convergence angle (TOC) is considered to have a direct influence on the retention of the crown with a significant reduction in retention after approximately 5 degrees (Jorgensen, 1955). The recommended values based on *in vitro* testing have ranged from as low as 2 degrees to 12 degrees for optimal retention and resistance form (Prothero, 1923; Jorgensen, 1955; El-Ebrashi et al., 1969; Gilboe & Teteruck, 1974; Kaufman et al., 1961; Wilson & Chan, 1978).

The achievability of recommended values were first reported in 1978 (Ohm & Silness, 1978). Dies prepared by dental students were found to have TOC values of approximately 20 degrees. These dies were measured by projecting the silhouette of the die and tracing around the shadow, with the axial walls extrapolated to measure the TOC angle. A large number of studies have tested the clinical achievability described with their associated measuring methods, which can be traced to those original investigators (Ohm and Silness, 1978; Leempoel et al., 1987; Kent et al., 1988; Nordlander et al., 1988; Noonan and Goldfogel, 1991; Annerstedt et al., 1996; Sato et al., 1998; Etemadi et al., 1999; Smith et al., 1999; Poon and Smales, 2001; Al-Omari and Al-Wahadni, 2004; Begazo et al., 2004; Dalvit et al., 2004; Ayad et al.,

2005; Okuyama et al., 2005; Patel et al., 2005; Rafeek et al., 2006; Ghafoor et al., 2011; Ghafoor et al., 2012; Aleisa et al., 2013; Alhazmi et al., 2013; Guth et al., 2013; Marghalani, 2014; Yoon et al., 2014). In recent years, the measuring methods have evolved from measuring a silhouette of a preparation to digital means as mentioned in a recent review (Tiu et al., 2015). This technology has become a valuable restorative technique and a useful tool in obtaining quantifiable data.

Conventional crown preparation recommendations were originally based on cemented metal-based restorations that considered zinc-based cements as the reference standard. Currently, manufacturer recommendations for ceramic crowns are approximately 12 degrees TOC with a minimum of 1 mm to 1.5 mm margin width in order to maintain sufficient ceramic thickness (Ivoclar Vivident; VITA Zahnfabrik H. Rauter GmbH & Co. KG,).

Teeth are complex and vary between each other, and a ceramic crown restoration is influenced by multivariate conditions (Rekow et al., 2006). In terms of geometry, the TOC, margin width, and abutment height are assumed to act and influence each other in maximizing the retention and resistance of the crown. Lacking in the literature are clinical studies that measure all these parameters and a single universal method of testing these parameters for ceramic restorations. To address this need for an objective measuring method, the coordinate geometry method was formulated with a set of rules outlined in a previous study (Tiu et al., 2014). In this study, a custom program was developed to automate many of the calculations in the methodology in order to apply the method to a large sample size.

With such a tool, a comprehensive analysis of crown preparations is presented in two parts using descriptive statistics. Part 1 report geometric parameters obtained from complete crown preparations. Part 2 applies commonly accepted retention and resistance form theories for this sample. This study also proposes a guide to future reporting methods on the geometry parameters of crown preparations.

6.2 Methods and Materials

Two hundred sixty-two second-poured complete crown preparations prepared for ceramic restorations (IPS e.max Press; Ivoclar Vivadent) were collected from dental laboratories located in towns and cities in efforts to represent the population in New Zealand. The period of collection was at each laboratory's discretion and all 262 specimens were pooled to eliminate any laboratory identifiers. Excluded from the pool were 26 specimens that displayed a negative or flat abutment height. These were deemed unconventional and eliminated after examination by an experienced specialist (B.A.).

A single technician (J.T.) prepared each specimen by exposing the finish lines, and each specimen was scanned in three dimensions (3D) (CeraMill map400; AmannGirrbach, accuracy 20 μm). Stereolithography (STL) datasets were extracted from the software and inserted into a general purpose 3D viewer (3D-Tool-Free; http://www.3d-tool-usa.com). Two cross-sectional images from each preparation were captured (faciolingual view [FL] and mesiodistal view [MD]) with the two planes 90 degrees around the assumption of a central axis. The images were uploaded into the custom computer program, which tracked the outlines into x-, and y- coordinates. By using prewritten formulae, the software was able to select specific points from which the geometric parameters were calculated (Tiu et al., 2014).

The software output the values for the geometric parameters, and the values were grouped according to tooth type (ISO 3950). This study uses descriptive statistics to display the average TOC angle for two cross sections (FL and MD), margin width for four sides (facial, lingual, mesial, and distal) and abutment height for four sides (facial, lingual, mesial, and distal) with their associated confidence intervals.

6.3 Results

The number of maxillary specimens (n = 185) was greater than the number of mandibular specimens (n = 51). The greatest number of preparations was for the maxillary left central incisor (n = 30), and the least number collected was for the mandibular central incisors, mandibular right lateral incisor, mandibular canines, mandibular left premolars, and right second molar teeth (n = 1). Mean TOC and 95% confidence intervals for each tooth are displayed in Table 6.I with pooled TOC values by type of tooth, as seen in figure 6.1. All mean TOC values are greater than the values recommended by Shillingburg et al. (2012), and the recommendations provided by manufacturers.

The mean TOC values for both FL and MD views on maxillary premolars were similar, except for the MD view the maxillary right first premolar (TOC = 43.89 degrees). The greatest mean TOC value was found on the maxillary left second molar (TOC = 74.49 degrees, n=4). Maxillary posterior preparations had larger confidence intervals compared to maxillary anterior preparations. Mean TOC values were lower for mandibular posterior preparations compared to maxillary preparations.

The marginal width with their associated confidence intervals for each tooth is displayed in Table 6.2 with pooled values as seen in figure 6.2. The lingual aspect of the maxillary left second molar, and the distal aspect of the left mandibular third molar had mean margin widths of 1.29 mm and 1.11 mm. All other mean margin widths were below 1 mm.

The height of preparations and associated confidence intervals for each tooth is provided in Table 6.3, with pooled values as seen in figure 6.3. Maxillary canines had the highest mean height (5.25 mm), with mandibular molar preparations displaying the shortest mean height (1.87 mm). The facial aspect of every tooth had the highest mean abutment height compared to the other views (lingual, mesial and distal). The mean

abutment heights for the mesial and distal aspects for each tooth are lower than facial and lingual aspects.

Table 6.1 Total occlusal convergence angles for each tooth prepared by general dentists.

			Molars		**Premolars**		**Canines**	**Incisors**		**Incisors**		**Canines**	**Premolars**		**Molars**		
Maxilla	MD	Mean	52.30	52.35	28.87	43.89	26.30	22.89	29.47	27.68	23.13	20.93	26.91	28.36	38.92	53.09	
		SD⁺	28.14	11.17	13.88	17.23	14.57	9.43	10.15	10.40	7.80	10.62	15.44	11.68	17.34	27.46	
		CI*	±24.67	±9.79	±6.80	±11.25	±7.92	±4.03	±3.70	±3.72	±3.95	±6.94	±10.70	±8.65	±8.78	±26.91	
	FL	Mean	51.28	30.19	29.90	28.54	46.08	38.74	43.60	42.83	36.92	46.17	23.53	33.83	37.68	74.49	
		SD⁺	32.05	9.66	14.24	11.02	7.86	8.48	7.94	9.55	6.13	6.59	11.02	9.35	15.88	27.57	
		CI*	±28.10	±8.47	±6.98	±7.20	±4.27	±3.63	±2.85	±3.42	±3.10	±4.30	±7.64	±6.93	±8.04	±27.02	
	N		5	5	16	9	13	21	29	30	15	9	8	7	15	4	
	Tooth		17	16	15	14	13	12	11	21	22	23	24	25	26	27	
	Tooth		47	46	45	44	43	42	41	31	32	33	34	35	36	37	38
	N		1	7	6	3	1	1	1	1	2	1	1	1	12	11	2
Mandible	FL	Mean	37.44	42.12	48.20	56.69	36.17	40.21	37.01	22.83	28.61	47.96	15.85	35.81	49.85	48.54	60.53
		SD⁺		25.44	36.58	20.63					7.79				23.41	18.43	24.34
		CI*		±18.84	±29.27	±23.34					±10.80				±13.25	±10.89	±33.73
	MD	Mean	48.06	51.73	34.43	48.35	27.55	20.63	22.87	15.09	21.74	23.92	18.17	58.78	48.08	46.34	68.30
		SD⁺		15.93	15.59	5.67					13.43				17.19	18.89	11.72
		CI*		±11.80	±12.48	±6.41					±18.61				±9.73	±11.16	±16.25

FL, faciolingual; MD mesiodistal; CI, confidence interval.
*Standard deviation for total occlusal convergence angle is shown for comparative purposes with previous studies.

Table 6.2 Margin width (mm) for each tooth prepared by general dentists

			Molars		**Premolars**		**Canines**	**Incisors**		**Incisors**		**Canines**	**Premolars**		**Molars**		
Maxilla	F	Mean	0.62	0.81	0.54	0.65	0.52	0.45	0.54	0.49	0.51	0.62	0.52	0.49	0.53	0.69	
		CI*	±0.24	±0.55	±0.10	±0.19	±0.14	±0.09	±0.09	±0.09	±0.10	±0.14	±0.19	±0.17	±0.10	±0.34	
	L	Mean	0.70	0.47	0.55	0.47	0.55	0.56	0.64	0.74	0.70	0.59	0.40	0.53	0.63	1.29	
		CI*	±0.21	±0.13	±0.08	±0.13	±0.12	±0.08	±0.07	±0.15	±0.13	±0.24	±0.15	±0.16	±0.19	±0.79	
	D	Mean	0.79	0.54	0.49	0.58	0.49	0.50	0.60	0.59	0.49	0.50	0.63	0.82	0.68	0.38	
		CI*	±0.16	±0.25	±0.07	±0.23	±0.11	±0.09	±0.12	±0.10	±0.08	±0.24	±0.13	±0.28	±0.18	±0.15	
	M	Mean	0.57	0.56	0.62	0.65	0.50	0.46	0.62	0.67	0.61	0.48	0.61	0.82	0.76	0.97	
		CI*	±0.18	±0.23	±0.13	±0.17	±0.07	±0.08	±0.11	±0.11	±0.12	±0.10	±0.22	±0.39	±0.24	±0.76	
	Overall Mean		0.67	0.60	0.55	0.59	0.52	0.49	0.62	0.62	0.58	0.55	0.54	0.67	0.65	0.83	0.67
	n		5	5	16	9	13	21	29	30	15	9	8	7	15	4	
	Tooth		17	16	15	14	13	12	11	21	22	23	24	25	26	27	
	Tooth		47	46	45	44	43	42	41	31	32	33	34	35	36	37	38
	n		1	7	6	3	1	1	1	1	2	1	1	1	12	11	2
	Overall Mean		0.66	0.74	0.73	0.69	0.54	0.47	0.40	0.41	0.53	0.70	0.50	0.44	0.71	0.69	0.71
Mandible	F	0.73	0.69	0.66	0.71	0.78	0.62	0.18	0.47	0.48	0.74	0.57	0.51	0.64	0.67	0.73	3.20
			±0.18	±0.30	±0.31					±0.01				±0.15	±0.32	±0.54	±0.98
	L	0.48	0.67	0.65	0.72	0.39	0.33	0.56	0.18	0.33	0.50	0.54	0.36	0.60	0.57	0.37	2.28
			±0.32	±0.29	±0.14					±0.32				±0.15	±0.18	±0.26	±1.66
	D	0.82	0.81	0.79	0.66	0.22	0.33	0.45	0.42	0.71	0.66	0.40	0.51	0.86	0.80	1.11	1.81
			±0.31	±0.22	±0.12					±0.42				±0.13	±0.20	±0.72	±0.38
	M	0.61	0.77	0.82	0.65	0.77	0.58	0.40	0.58	0.60	0.88	0.47	0.39	0.73	0.89	0.64	2.26
			±0.17	±0.30	±0.06					±0.10				±0.22	±0.40	±0.52	±0.59

F, facial; L, lingual; D, distal; M, mesial; CI, confidence interval.

Table 6.3 Abutment height (mm) for each tooth prepared by general dentists

			Molars		Premolars		Canines	Incisors		Incisors		Canines	Premolars		Molars		
Maxilla	B	Mean	3.39	2.58	4.43	4.99	7.08	6.06	6.26	6.20	5.97	6.69	4.51	3.61	4.11	2.69	
		CI*	±1.23	±1.91	±0.74	±1.19	±0.72	±0.48	±0.38	±0.36	±0.38	±0.76	±1.06	±0.61	±0.64	±0.63	
	L	Mean	2.67	4.05	3.01	3.41	5.69	4.39	4.95	4.56	4.52	4.32	3.01	2.79	3.05	2.33	
		CI*	±0.77	±0.61	±0.51	±1.04	±0.64	±0.55	±0.42	±0.73	±0.60	±0.87	±0.70	±0.63	±0.39	±0.51	
	D	Mean	2.79	2.56	2.21	1.85	4.06	4.08	3.74	3.73	3.77	4.06	2.41	2.46	2.64	2.63	
		CI*	±0.67	±0.67	±0.49	±0.49	±0.39	±0.56	±0.44	±0.38	±0.36	±0.56	±0.45	±0.81	±0.55	±0.51	
	M	Mean	1.93	2.86	2.96	2.56	4.18	4.26	3.95	3.71	4.01	3.79	2.34	2.19	2.58	1.82	
		CI*	±0.48	±0.69	±0.73	±0.55	±0.51	±0.56	±0.43	±0.38	±0.39	±0.59	±0.66	±0.59	±0.48	±0.20	
	Overall	Mean	2.70	3.51	3.15	3.20	5.25	4.70	4.73	4.55	4.57	4.72	3.07	2.76	3.10	2.37	
	n		5	5	16	9	13	21	29	30	15	9	8	7	15	4	
	Tooth		17	16	15	14	13	12	11	21	22	23	24	25	26	27	
	Tooth		47	46	45	44	43	42	41	31	32	33	34	35	36	37	38
	n		1	7	6	3	1	1	1	1	2	1	1	1	12	11	2
	Overall	Mean	1.87	2.66	2.48	2.68	4.76	4.13	3.71	3.53	4.13	3.94	3.94	2.98	2.94	2.75	2.39
Mandible	B	Mean	3.12	3.48	3.52	3.38	6.24	4.37	4.04	3.90	4.74	4.86	5.92	5.57	3.99	3.64	3.20
		CI*		±1.07	±1.16	±0.39					±1.03				±1.16	±0.47	±0.98
	L	Mean	1.72	1.92	2.13	2.61	5.50	4.82	4.06	3.26	3.57	3.87	4.60	1.72	2.85	2.52	2.28
		CI*		±0.74	±0.68	±0.75					±1.72				±0.94	±0.56	±1.66
	D	Mean	0.76	2.76	2.58	3.12	4.85	3.79	3.43	4.12	4.24	2.39	1.98	2.62	2.76	2.15	1.81
		CI*		±0.68	±0.46	±0.32					±0.67				±0.62	±0.49	±0.38
	M	Mean	1.86	2.47	1.69	1.62	2.43	3.55	3.32	2.82	3.98	3.09	3.24	2.00	2.14	2.69	2.26
		CI*		±0.52	±0.51	±0.17					±0.52				±0.48	±0.48	±0.59

F, facial; L, lingual; D, distal; M, mesial; CI, confidence interval

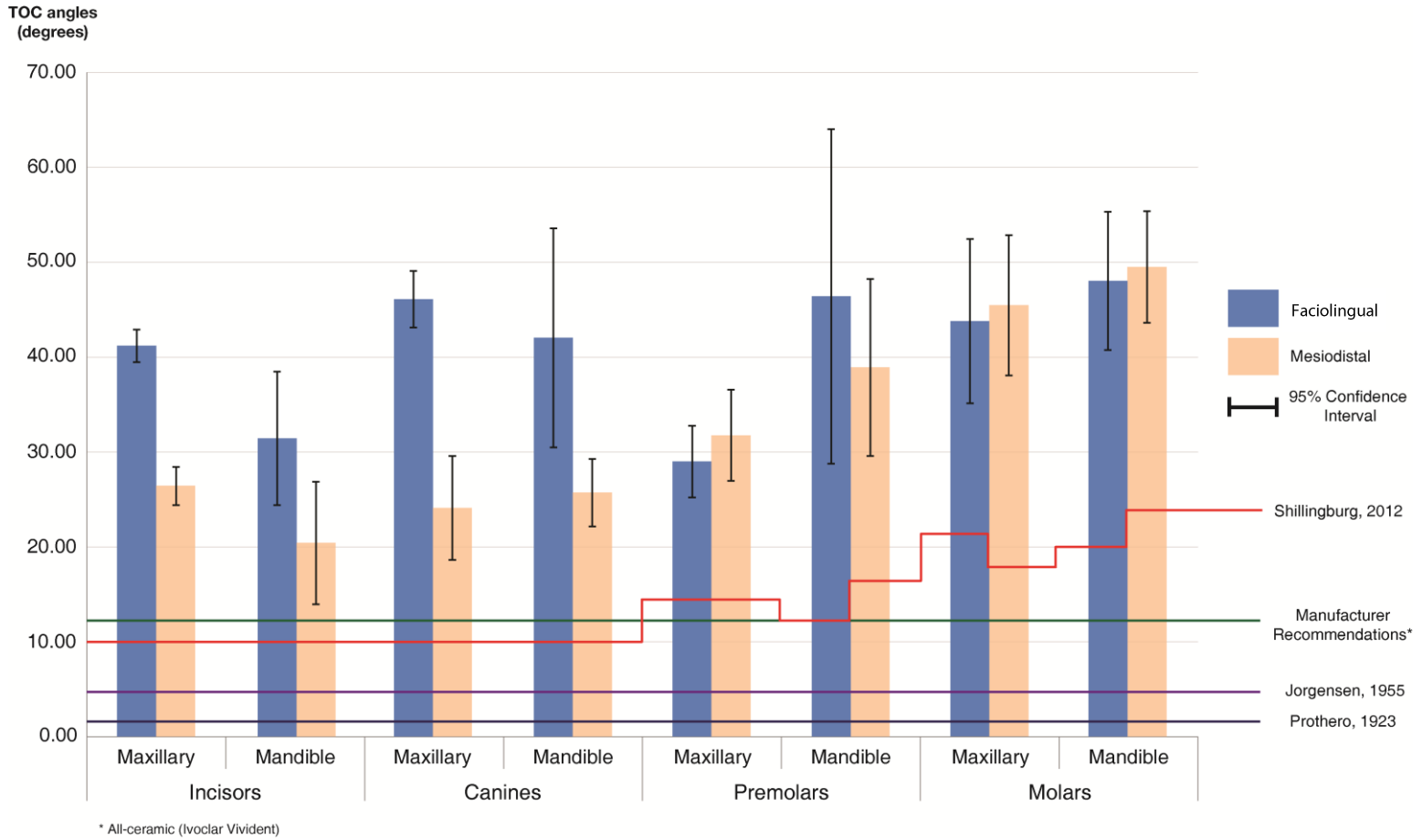


Figure 6.1 Mean total occlusal convergence angles with 95% confidence intervals grouped into type of teeth and compared to recommended values found in literature

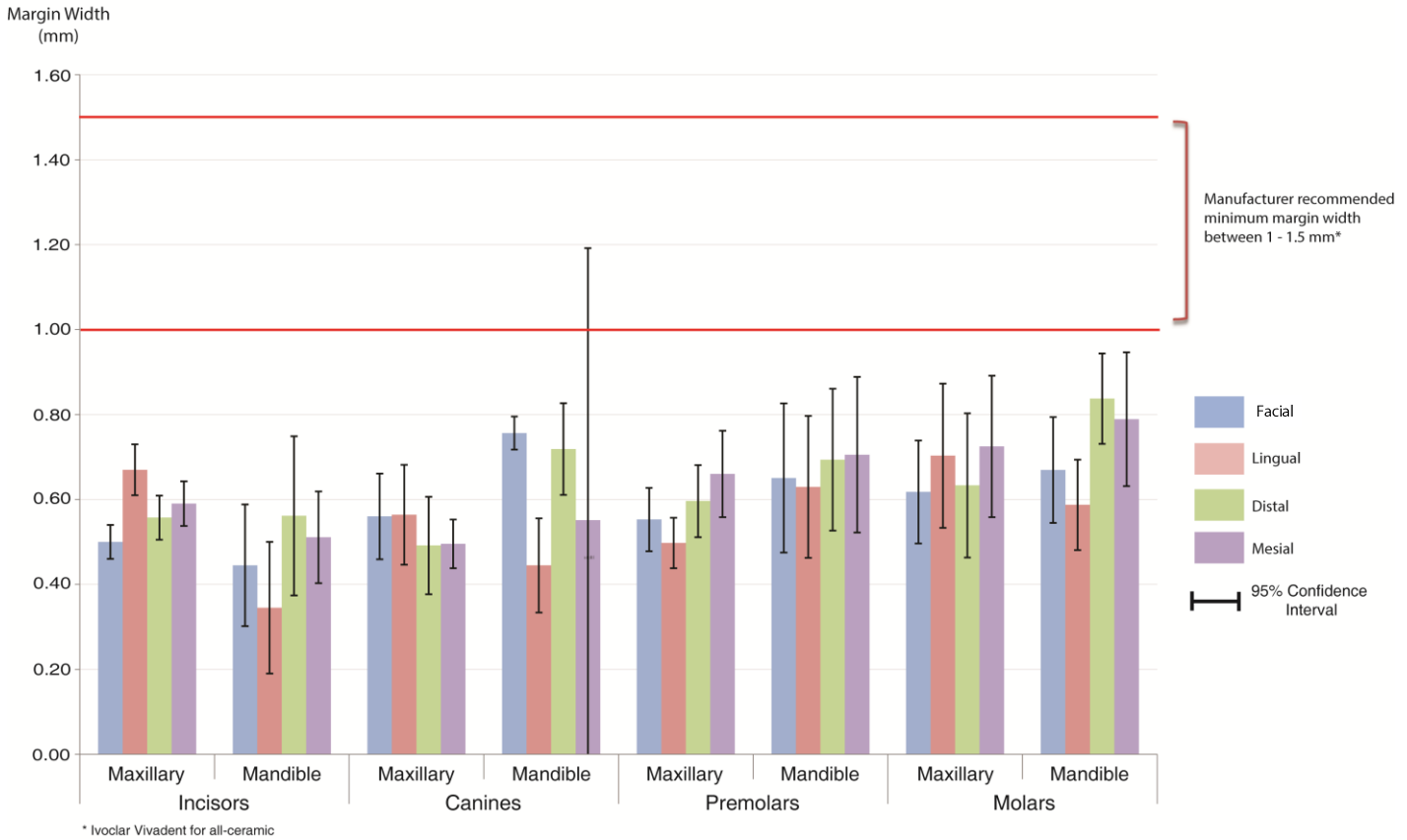


Figure 6.2 Mean margin width with 95% confidence intervals grouped into type of teeth and compared to current recommendations

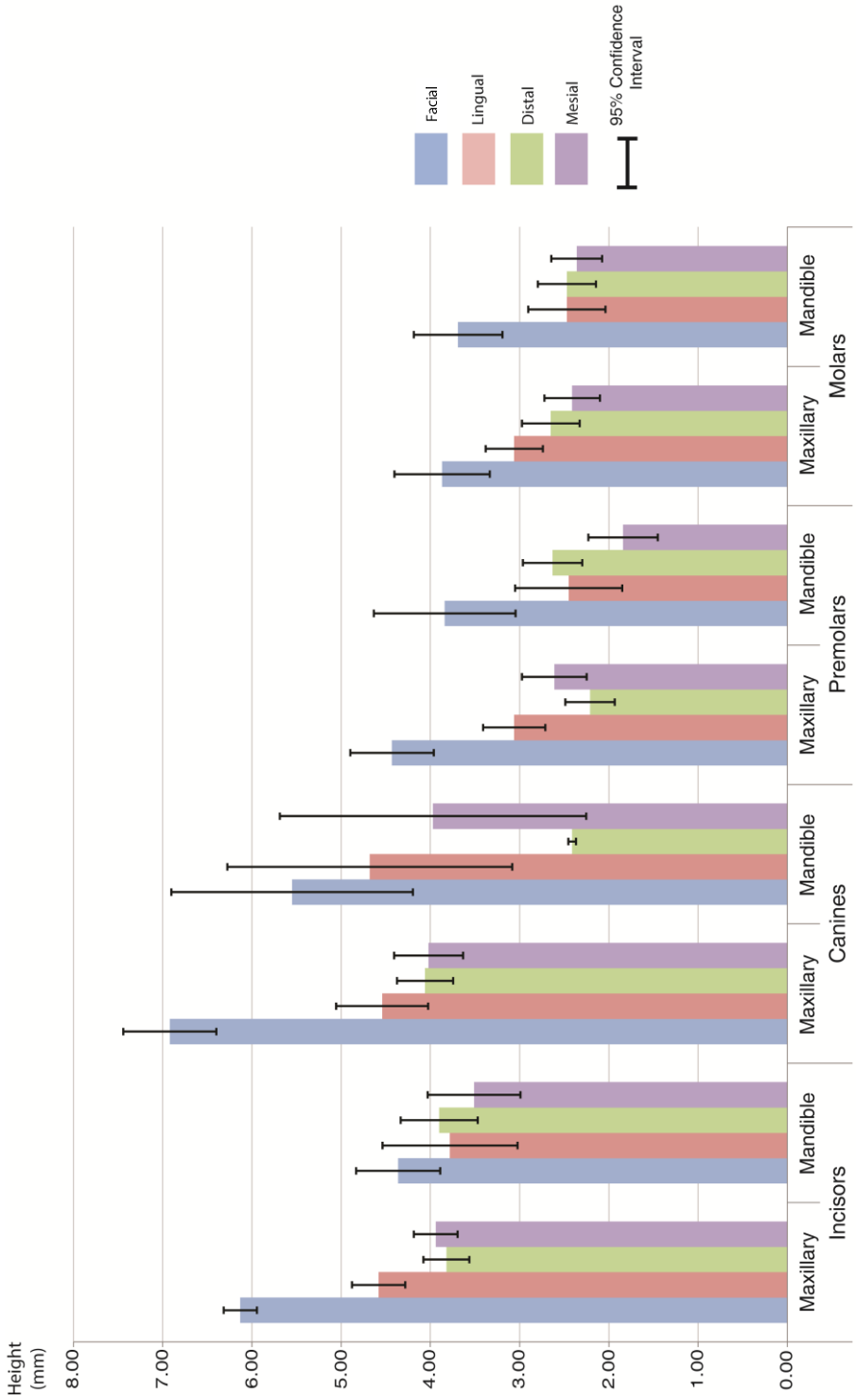


Figure 6.3 Mean abutment height values with 95% confidence intervals for each tooth

6.4 Discussion

This study presents results of TOC, margin width, and abutment height measurements made from clinically produced preparations for lithium disilicate-based ceramic complete crowns. The values show a significant discrepancy between the clinical situations and recommended values.

The average TOC values were above the manufacturer recommended values of 12 degrees. It was evident the FL cross sections of maxillary incisors were naturally shaped in a way that prevented the 12 degrees from being achieved. A preparation following the natural taper of an incisor would produce a corresponding greater TOC angle. Results confirm this inspection, showing that all maxillary anterior specimens had an average FL cross-section with higher TOC values compared to the average MD cross-sectional TOC values. Premolars and molars for both maxillary and mandibular preparations displayed similar average TOC values between the two cross-sectional views. Posterior teeth appear to be more uniform and cube like in both views when compared to anterior teeth, which appear flatter. Mandibular incisors show a wider confidence interval; however, only five dies were included in this sample as opposed to the maxillary incisors (n= 94). The greatest mean TOC was for the right maxillary second molar (74.49 degrees, 95% confidence interval = 27.02, n = 4). Teeth with low number of specimens are not representative of the respective preparations by dentists in New Zealand.

More studies have been published on the TOC angle than any other parameter, which reflects the emphasis on this parameter for clinical success. Almost all previous studies published report mean TOC angles above recommendations found in the literature. This report in particular, observed very high TOC angles for maxillary and mandibular molars. There are previous studies which also provide similar values (27.03 degrees, SD = 15.00 (Patel et al., 2005); 30.44 degrees, SD 10.61 (Ghafoor et al., 2011); 37.20 degrees, SD = 13.50 (Al-Omari & Al-Wahadni 2004)).

The margin width values were below manufacturer recommendations for lithium disilicate ceramic crowns (1.0 to 1.5 mm). Many of the marginal widths fell within a range of 0.4 to 0.6 mm (figure 6.2), a range commonly associated with preparations for complete metal crowns. Although many preparations had margins short of the recommended values, there was a limitation given the size of the original tooth. Mandibular incisors and maxillary lateral incisors are smaller teeth, and a minimum margin of 1 mm would have taken too much existing tooth forms away. Clinicians are apparently conservative when it comes to crown preparation margin widths.

The clinician has the least control over the height of the preparation. The tooth requiring restoration may have previous damage that must be removed. In consideration of this, a general pattern of longer anterior preparations compared to posterior preparations must be considered. Previous studies measuring preparation height show a range of measurements but cannot be compared because the definition of height has not been adequately addressed (Sato et al., 1998; Etemadi et al., 1999; Guth et al., 2013). The methodology in this study allows for differentiating the height at different areas of the preparations. The height was higher for facial areas compared to mesial, distal, and lingual across all types of tooth preparations. The margin angle and abutment width are parameters that may be measured by the coordinate geometry method; however, these parameters were omitted in the current study.

It is unknown to the authors how many dentists contributed to the specimen collection and if the value constitutes an ideal representation of clinicians. The TOC values presented were far beyond the recommendations presented in the literature and under prepared for margin width. Findings in this study and others confirm that the recommended values for single bonded ceramic crowns may need to be revised.

The software used in this study may be developed for further measurements. If all future studies were performed in such a way, methodological differences would be negligible

allowing for meta-analysis. Currently the articles published have described many different methods and because of this, the values cannot be easily compared.

The numeric values produced in this study can be used as a base for future studies including *in vitro* testing. Many *in vitro* studies simulate TOC values up to a 32-degree maximum (Ayad et al., 1997; Zidan & Ferguson, 2003; Cameron et al., 2006). From this study, 32 degrees does not represent the upper limit of TOC values of preparations, which are in reality much higher. What happens to the resulting restoration when TOC is greater is unknown. Moreover, research is needed to test all these parameters together and how they influence each other and the resulting survival of the crown.

Another consideration is that the current recommendations of 12 degree TOC and a 1 mm margin may need to be reinvestigated and updated to a more clinically achievable value. Teeth are complex and unique, and no tooth should be subjected to the same recommended values. Each tooth needs its own clinically recommended value that is adjusted to the capacity of the tooth.

The authors recommend that future *in vitro* and *in vivo* studies involving the measuring of tooth preparations be prepared and reported in a manner similar to this study. Points to consider include: Specifying the material and type of crown (in this report, all preparations have been prepared for all-ceramic lithium disilicate complete crowns), type of cement used, type of tooth (e.g. ISO 3950 or FDI system which specifies the exact tooth and position in arch), number of specimens (n), reporting the means and confidence intervals, reporting the major parameters of TOC, margin width, abutment height, and abutment width; and reporting for each cross section or side (e.g. TOC, both the FL and MD views are specified and reported separately, margin width of mesial, distal, facial, and lingual margins).

Furthermore, future clinical trials should include the recording of preparation parameters for each individual preparation. Bringing this to practice would help standardise survival decisions.

6.5 Conclusions

With the limitations of this study, the following conclusions can be drawn:

1. Software is a useful tool for measuring crown preparation geometries. The TOC angles from preparations produced in general practices have values that are much higher than those recommended in the literature, the average width of marginal reduction on all teeth is greatest on facial surfaces, and all margin widths fall short of the minimum recommended 1 mm to 1.5 mm,
2. Predicting the effects of the observed shortfalls on the clinical longevity of restorations is impossible without clinical trials implementing an objective measuring method.

07

Measuring clinical crowns (2/2)

This chapter is a continuation of the previous chapter. The purpose of this study is to measure the theoretical retention and resistance of clinically produced complete crown preparations using an objective measuring method. This chapter is a published manuscript inserted in its entirety.

Janine Tiu, Basil Al-Amleh, J Neil Waddell, Warwick J Duncan. Reporting numeric values of complete crowns. Part 2: Retention and Resistance theories. Journal of Prosthetic Dentistry 2015: DOI:10.1016/j.prosdent.2015.01.007. – 1.42 Impact Factor

7.1 Introduction

Clinicians use tooth preparation principles to maximize the retention and resistance of complete crowns. This in turn is thought to influence the longevity and survivability of the restoration. Manufacturers have provided recommendations in order to produce an ideal preparation that maximises the retention and resistance form of the prepared tooth. According to the "Glossary of Prosthodontic Terms, (2005)" retention is the ability to resist removal along the path of insertion, and resistance is the ability to prevent dislodgement by oblique or horizontal forces. In practice, both retention and resistance are closely related and is described as phenomena that cannot be separated. Several factors are under the control of the operator during tooth preparation and known to affect retention and resistance. These include the total occlusal convergence (TOC) angle, total surface area, surface roughness, preparation height and width, and auxiliary features such as boxes or grooves (Goodacre et al., 2001; Heintze, 2010).

Parameters of ceramic lithium disilicate complete crown preparations by general dentists such as TOC, preparation height, and margins width were collected and reported in part 1 of this study. The TOC angles produced were always greater than the recommended angles for both anterior and posterior teeth, and that preparation widths were always less than the recommended minimal width of 1 mm. In part 2 of this study, conventional retention and resistance theories and formulae found in the literature were applied to predict clinical serviceability. Total surface area affects the amount of area for the bonding cement and is an important factor in crown retentive tests. The greater this area is, the greater the retention of the restoration will be. Several studies have published surface area of *in vitro* retention tests of standardised abutments or preparations using adaptation of foil and directly measuring (Swift et al., 1997; Wolfart

et al., 2003), or weighing the applied foil (Dahl & Oilo, 1986; Ernst et al., 1998; Ernst et al., 2005). A simplified way of measuring surface area is by approximation and the assumption that the preparation abutment resembles a truncated cone/cone frustum (CF), or a right truncated pyramid (RTP) (figure. 7.1) (Arconia et al., 1990; Chan et al., 2007; Bowley & Kieser, 2007; Sipahi et al., 2007). To the authors' knowledge, no clinical studies measuring each individual surface area of crown preparations have discussed their long-term effects on the resulting restoration, despite the fact that the bondable and cementable surface area of an abutment plays a major role in clinical serviceability.

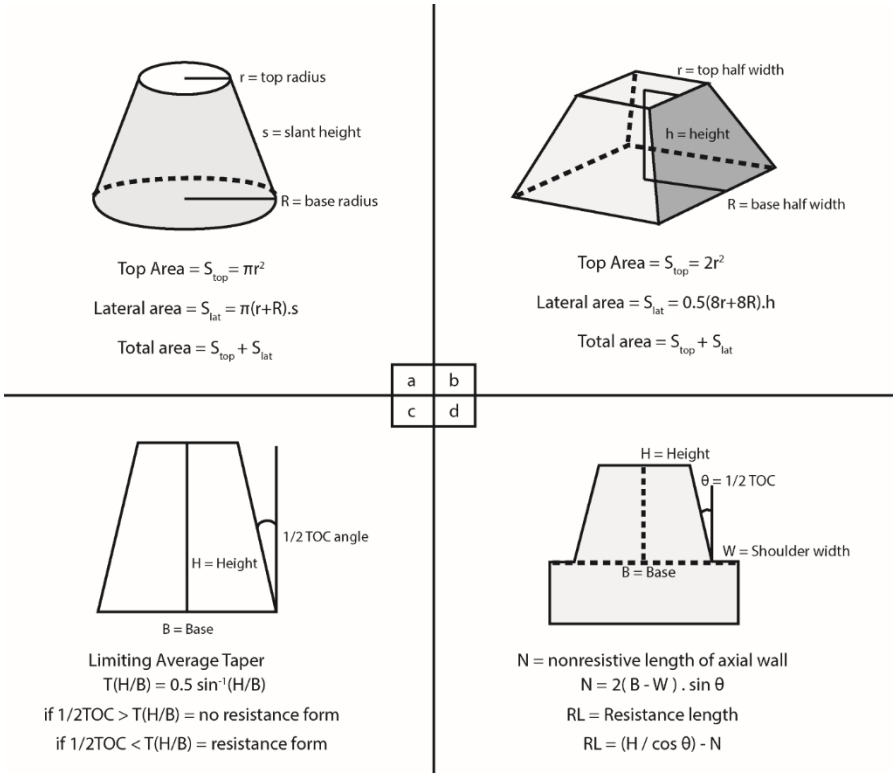


Figure 7.1 Formulas used. A, Cone frustum. B, Right truncated pyramid. C, Limiting taper. D, Resistance length.

Preparation parameters considered individually cannot predict the success of a restoration. For this reason, combining these features and attempting to discover their combined effects with varying angles and lengths has been the subject of many studies.

Currently, a few quantifying methods and theories have been introduced in the literature with many regarding the quantification of the resistance form as an important factor to influence the success of a restoration (Caputo & Standlee, 1987).

Resistance form depends on the direction and magnitude of the oblique force, the preparation geometry and the luting agent used to cement the crown. Woolsey and Matich (1978), evaluated the effect of the preparation height and taper on the resistance form and found that a reduction in the convergence angle increased the resistance form. They also found that the addition of grooves provided resistance to horizontal dislodgment, which was also confirmed by Potts et al. (1980).

Dodge et al. (1985), tested the effect of the convergence angle on the retention and resistance form and found that resistance form was more sensitive to changes in convergence angle. Owen (1986), reviewed the literature and stated that while proximal grooves contributed to the resistance form, the minimum required clinical taper value was still unknown.

Zuckerman (1988), introduced a method of calculating resistance forms by using a boundary circle. This concept is based on the width of the base of the abutment and whether the rotation of the crown is higher or lower than the height of the cusp. This was taken further in the concept of the Limiting Taper, which was introduced by Parker et al. (1988; 1991; 1993). This method applies a mathematical formula based on the height-to-base ratio of a preparation to determine the preparation's resistance form characterized as the limiting taper. The resistance form is based on an arc of the restoration pivoting about a point on the opposite side. If the TOC value is within the limiting taper, then that side of the restoration is considered to have a resistant form. If it is higher, then that side is considered not to impart resistance to dislodgement of the restoration by oblique forces. The idea is an "on" or "off" concept. Clinical acceptability requires the preparation to have resistance form in all directions – the facial, lingual, mesial and distal sides.

Trier et al. (1998), showed that failed castings were found on abutments that lacked resistance form and that the clinical success reflected the all or none nature of resistance form in accordance with the limiting taper theory. Cameron et al. (2006), looked at the limiting taper concept versus the linear or progressive relationship and found an abrupt change in the graph of the cycles it took to dislodge the crowns as a function of taper. This suggested that it was reasonable to use the limiting taper as a guideline for minimally acceptable preparation.

The limiting taper concept was disputed by Wiskott et al. (1996; 1997), who showed that the relationship between the taper and the resistance form and the abutment height and resistance form is approximately linear. The linear relationship was suggested to be directly influenced by the length of the axial wall that provided resistance. A formula for this length is provided by the study by Leong et al. (2009). For the purposes of this study, this theory will be called the resistance length theory.

In theory, all these factors play their part in increasing retention and resistance. Ideally, measuring clinical crown preparations and finding their values for surface area, Limiting Taper, or Resistance Length should give an indication of the retention and resistance of the tooth preparation. The greatest barrier to measuring clinical crown preparations has been the lack of an ideal, simple, objective, and universally accepted measuring method.

In part 1, a custom program was created based on the coordinate geometry method (CGM)(Tiu et al., 2014). This methodology objectively measures abutment geometry parameters in a convenient manner by using computer-aided design scanned images of the abutments. Simple geometric parameters of a large number of clinical cases are easily attainable using the CGM method. The purpose of this study was to show how the CGM methodology could also obtain information for calculating the surface areas using both CF and RTP methods, and for determining the resistance forms of each crown abutment by implementing the most accepted crown resistance theories; the Limiting Taper and Resistance Length theories.

7.2 Material and methods

A total of 236 all-ceramic lithium disilicate (IPS e.max Press, Ivoclar Vivadent, Liechtenstein) complete crown preparations made by general dentists were prepared and scanned in 3 dimensions as described in the Part 1. Stereolithography (.STL) datasets were extracted from the software and inserted into a general purpose 3D viewer (3D-Tool-Free, www.3d-tool-usa.com). Two cross-sectional images from each preparation were captured (buccolingual (BL) and mesiodistal (MD) views) with the two planes 90 degrees around the assumption of a central axis. The images were uploaded onto custom computer software using the CGM which automatically tracked the outline of the images into x- and y- coordinates.

Surface areas using the CF and RTP approximations were calculated with their respective confidence intervals and limiting taper and resistance length were calculated with formulas as seen in figure 7.1.

7.3 Results

The pooled mean surface area as seen in figure 7.2 and individual numeric values are presented in Table 7.1. Each tooth had approximated values using the CF and RTP, with clear differentiation of the top surface area and the lateral surface areas. Mean surface areas for mandibular preparations from central incisors to 2nd premolars are less than their maxillary counterparts, whereas the maxillary and mandibular molars have close mean values. Incisors have less occlusal/top surface areas compared to premolars and molars. The lowest mean surface area is seen in mandibular central incisors (CF = 33.97 mm^2, RTP = 41.75 mm^2) while the largest mean surface area is seen in the maxillary second molar (CF = 105.44 mm^2 RTP = 117.50 mm^2). The lateral surface area for

maxillary incisors and maxillary molars are similar as the increase is attributed to a larger top surface area.

The resistance length and limiting taper for premolars were calculated as seen in figure 7.3, and molars are presented as seen in figure 7.4. The resistance length is presented individually as dots on the left while the limiting taper is represented as percentages on the right. The highest overall percentage of preparations that show resistance form are the maxillary premolars, with at least 30% of all maxillary premolar preparations showing resistance form. The facial aspect of all posterior teeth show the highest percentage resistance forms compared to all other aspects.

Table 7.1 Mean surface area in mm^2 (cf = cone frustum, rtp = right truncated pyramid, lat = lateral surfaces, top = top surface area)

			Molars		**Premolars**		**Canines**	**Incisors**		**Incisors**		**Canines**	**Premolars**		**Molars**		
Maxilla	CF	Lat	81.77	78.05	61.82	69.06	92.69	69.47	76.47	73.56	60.56	77.23	68.44	57.57	77.58	63.42	
		Top	33.14	20.88	14.25	15.54	7.14	6.47	7.50	6.04	3.75	7.05	20.05	18.93	27.62	30.18	
		Total	114.91	98.93	76.07	84.59	99.83	75.94	83.96	79.60	64.31	84.28	88.49	76.50	105.20	93.61	
		CI*	±34.52	±16.54	±9.81	±21.79	±14.43	±17.27	±8.85	±5.53	±17.05	±16.34	±19.44	±38.32	±10.78	±11.29	
	RTP	Lat	82.71	83.65	63.44	65.33	92.85	73.12	81.02	76.87	63.02	81.94	68.80	59.21	83.28	69.81	
		Top	42.20	26.58	18.15	19.78	9.09	9.23	9.54	7.69	4.78	8.97	25.53	24.10	35.17	38.43	
		Total	124.91	110.24	81.59	85.11	101.94	81.35	90.56	84.56	67.80	90.91	94.33	83.31	118.45	108.24	
		CI*	±39.96	±21.25	±11.38	±19.46	±11.52	±14.95	±9.20	±6.66	±14.25	±18.19	±18.72	±38.77	±12.63	±7.88	
	n		5	5	16	9	13	21	29	30	15	9	8	7	15	4	
	Tooth		17	16	15	14	13	12	11	21	22	23	24	25	26	27	
	Tooth		47	46	45	44	43	42	41	31	32	33	34	35	36	37	**38**
	n		1	7	6	3	1	1	1	1	2	1	1	1	12	11	**2**
Mandible	CF	Lat	50.67	71.40	60.58	52.46	77.27	37.19	30.94	30.90	49.03	53.66	77.90	69.93	77.21	72.32	**72.75**
		Top	31.58	30.01	17.95	9.55	5.84	1.68	2.36	3.74	4.47	5.32	14.26	11.33	28.60	25.66	**24.15**
		Total	82.25	101.41	78.53	62.01	83.11	38.87	33.30	34.64	53.50	58.98	92.16	81.26	105.80	97.98	**96.91**
		CI*		±21.71	±28.59	±42.58					±25.79				±23.03	±18.22	**±18.70**
	RTP	Lat	52.15	76.32	56.62	50.76	79.05	43.44	36.41	39.32	56.01	55.02	76.71	58.22	80.79	74.18	**67.62**
		Top	40.20	38.20	22.86	12.15	7.444	2.14	3.00	4.76	5.70	6.78	18.16	14.43	36.41	32.67	**30.75**
		Total	92.36	114.53	79.48	62.92	86.49	45.58	39.41	44.08	61.70	61.80	94.87	72.65	117.20	106.86	**98.38**
		CI*		±92.36	±28.40	±36.35					±24.76				±23.96	±18.79	**±16.22**

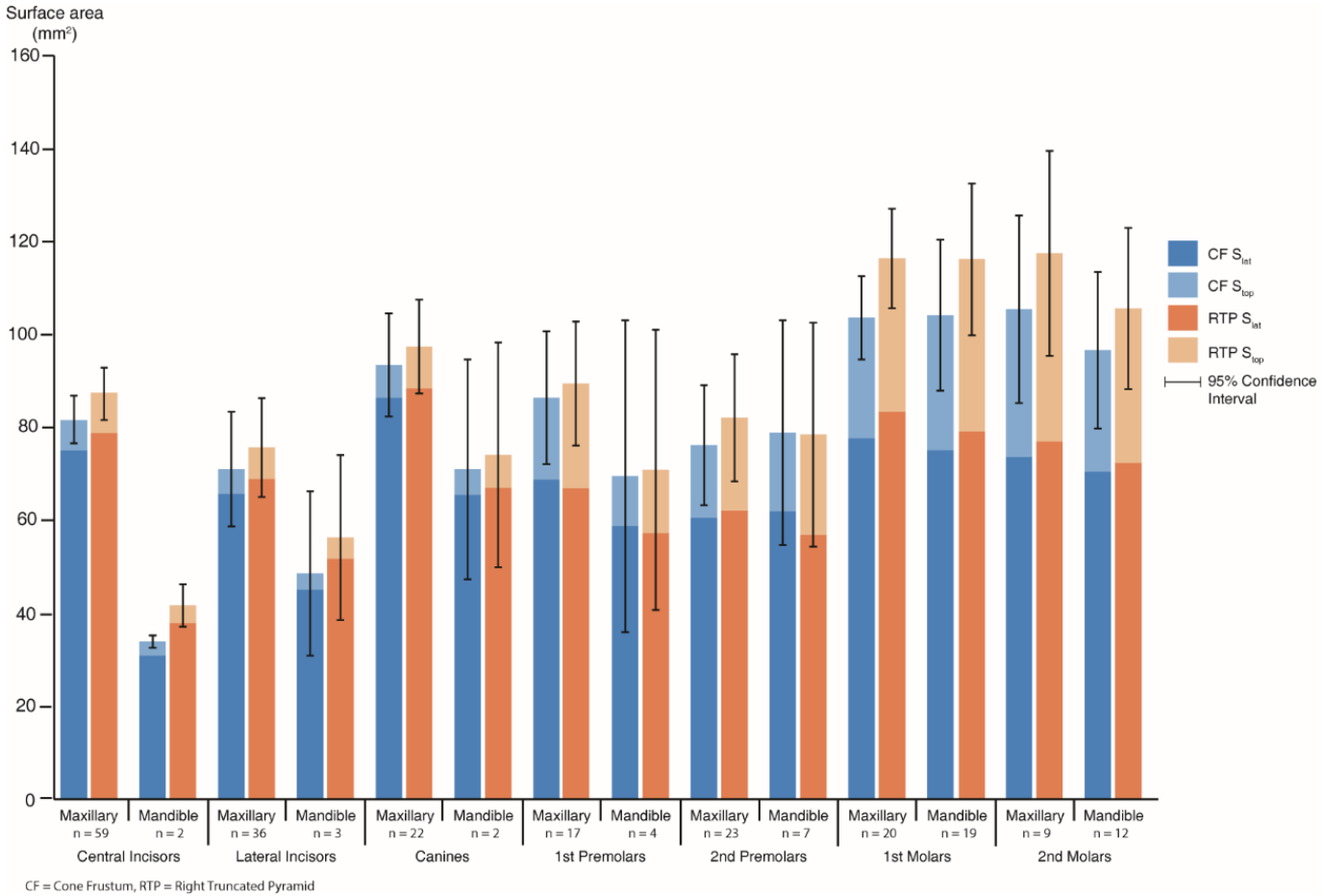


Figure 7.2 Mean surface area of each tooth using cone frustum and right truncated pyramid formula with dividing lateral and occlusal surface area and corresponding 95% confidence interval. CF, cone frustum; RTP, right truncated pyramid.

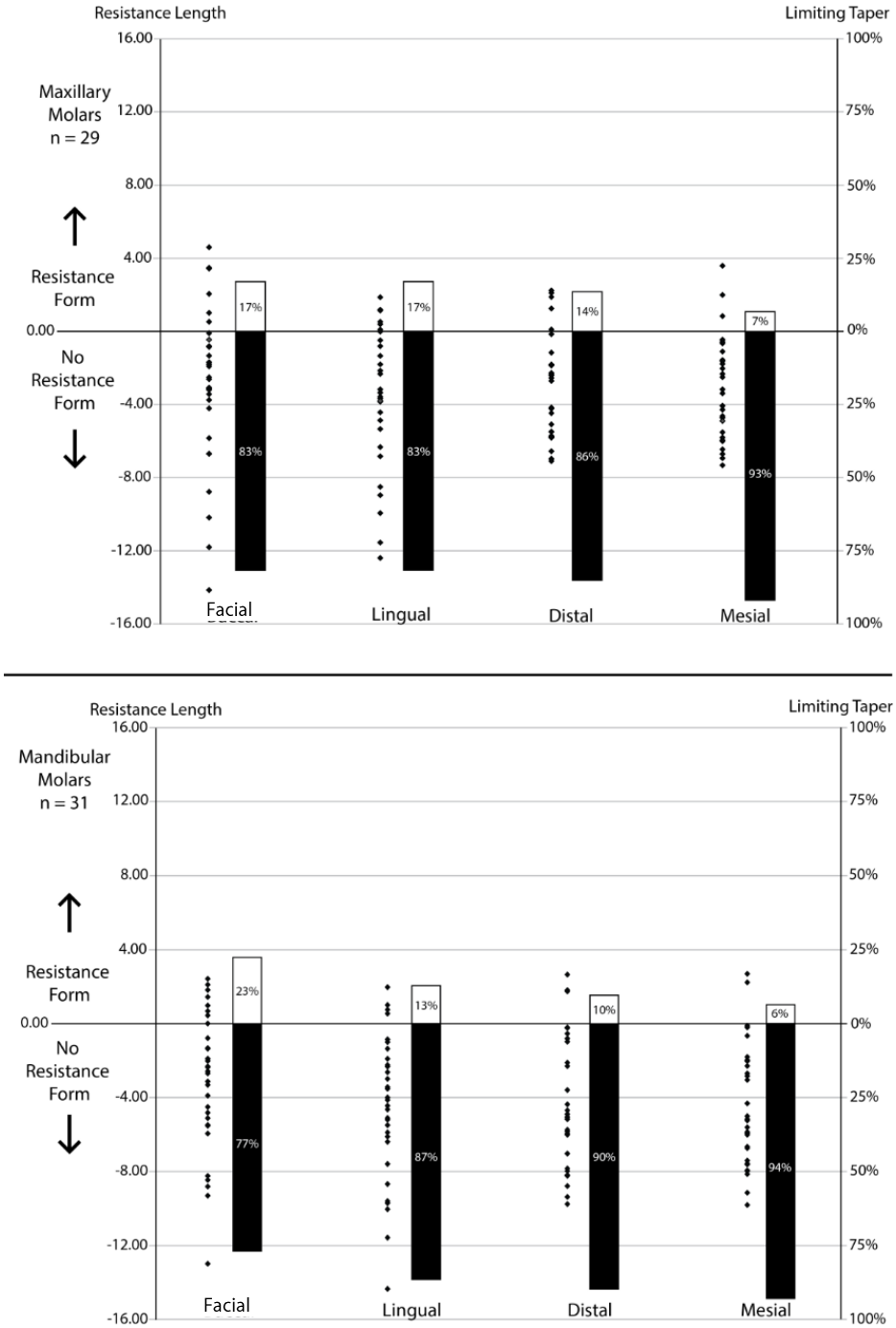


Figure 7.3 Resistance lengths in plots (left) versus limiting taper in percentages (right) for four planes of premolar tooth preparations.

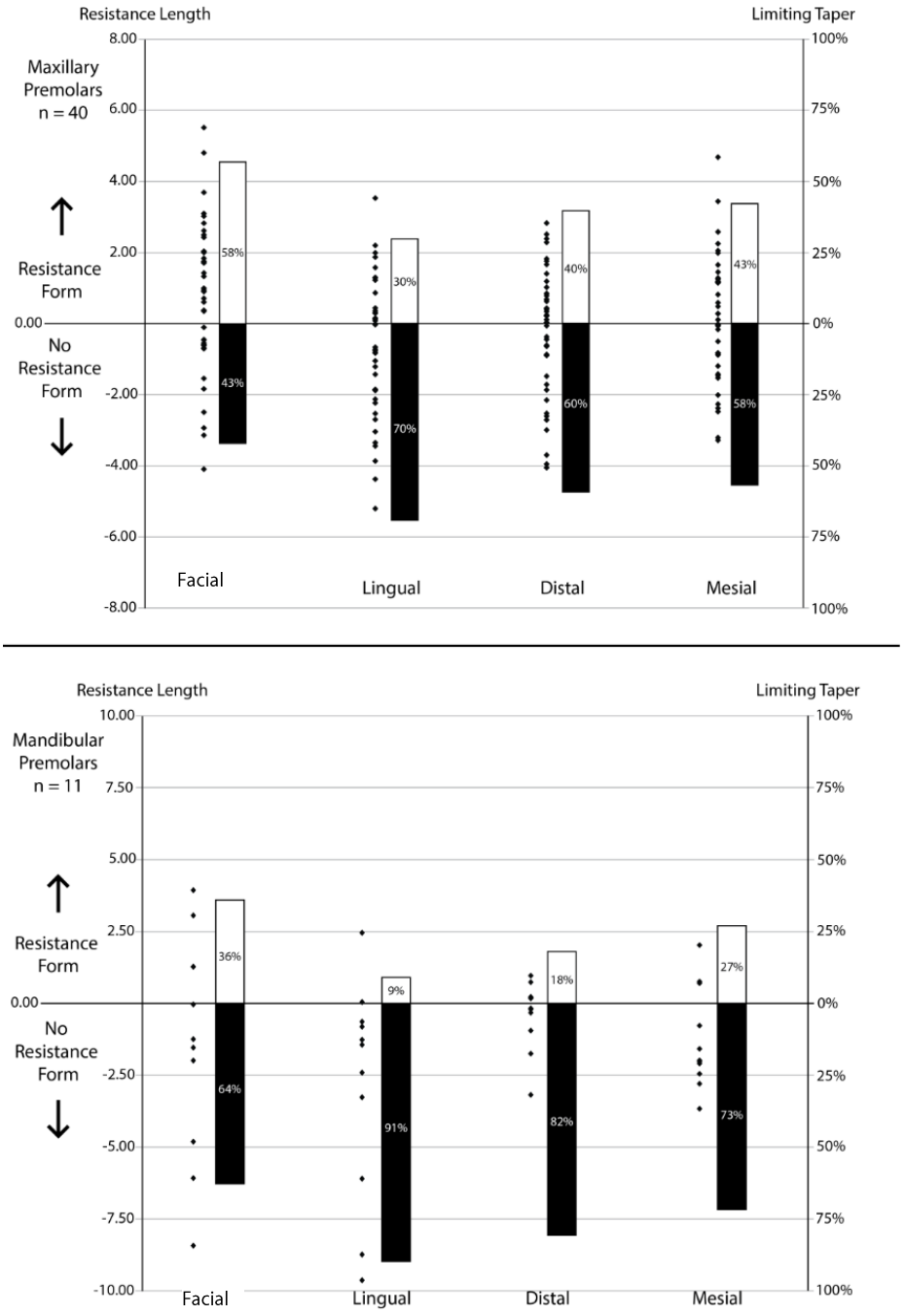


Figure 7.4 Resistance length in plots (left) versus limiting taper in percentages (right) for four molar preparations

7.4 Discussion

These results provide the numeric data for surface areas, limiting tapers and resistance lengths for a large number (n = 236) of clinically produced complete crown preparations. The method used in this study is shown to be useful in determining and quantifying the parameters of a preparation without the need for conventional sectioning and tracing processes. The method takes theories presented in the literature and provides the values for actual clinical preparations using a simple 3D scan. These retention and resistance theories, based on the geometric parameter of a preparation can be put to the test to determine their correlation to clinical preparations and their supposed survival potential.

The findings for surface area showed that using the RTP formula always resulted in a higher overall surface area. The top and lateral surface areas are affected by different forces, which is why they were presented separately as shown in a previous publication (Chan et al., 2007). The lateral surface area values for molars were very similar to the study by Chan et al. (2007), but the top surface area was noticeably less. This is because the molars used in this study had higher TOC values resulting in less occlusal surface area. This in turn leads to a smaller top surface area available for bonding.

This study presents the limiting tapers and the resistance lengths together for premolars and molars. Many of the premolars and molars failed to provide any resistance form for both theories. The reason can be traced back to the TOC values as both formulae rely on this value. Furthermore, the percentages and plots do not add up across all four sides showing that on a single preparation there are areas of no resistance and areas that provided resistance. Because clinically acceptable preparations require all four sides to exhibit resistance, the percentage of unacceptable teeth is much higher. The effects this has on a preparation and the resulting restoration with uneven distribution of resistance area is unknown.

Clinicians should be aware of the effects a larger TOC angle has on the amount of surface area available for bonding, and the resulting resistance form of a preparation. This study gives an alarming indication that many clinical complete crown preparations are failing to provide any resistance and are relying on other factors (such as the bonding system) to provide the majority of the resistance.

Much debate is evident in the literature as to the absoluteness of the limiting taper and the more linear indication of resistance length. Their correlation is evident, but can a higher resistance length give an indication of a superior clinical performance? The custom software created in this study provides an excellent way of measuring clinical crowns and applying these theories. Clinical studies could include measuring preparation parameters so that one day the debate about the resistance theories can be put to rest.

The authors recommend clinical trials implementing the methodology used in this study or a similar objective measuring method to record and observe these parameters to understand how to maximise retention and resistance for the long-term success of a restoration.

7.5 Conclusions

Although this study does not give clinical implications of such retention and resistance theories, the CGM methodology provides an ideal platform and useful tool in determining such implications for future *in vitro* retention tests and clinical trials

08

Part 1 Conclusions

8.1 Summary

Part 1 of this thesis started with a literature review outlining the need for an objective measuring method to measure the important clinician-controlled tooth preparation parameters. A thorough review identified the different methods used in the past has not substantially changed in the present day and found all the methods are inherently subjective. This produced the first aim:

1. To develop a validated objective measuring method for measuring crown preparation geometry

A theoretical model, which included formulae to reduce the subjectiveness in measuring methods, was created and further validated. This was then applied to software where further mathematical development was performed.

The software was named 'Preppr™' and was created to accept STL files and produce reports on the geometric dimensions of a tooth preparation. Most importantly – the total occlusal convergence angles and the marginal widths. This software was used to measure preparations prepared by general dentists to discover the real conditions of tooth preparations. This supported the second aim:

2. To report on the preparation geometry of tooth preparations by dentists

Important geometric parameters were measured as well as applied to work out retention and resistance – which previously existed as theory and never applied to clinical situations.

8.2 Software

In developing a validated objective measuring method to report on the preparation geometry of tooth preparations, software was unintentionally produced. This software was explored further in studies indirectly related to the aims of this thesis in two separate studies and therefore not included in the thesis (see appendix). These studies are published refereed abstracts and manuscripts currently under review.

8.3 Further studies

The development of software has identified a way to move forward with understanding the effects of crown preparation geometry. As more and more scanned dental information is collected and stored digitally, this software has the potential to carry out retrospective clinical audits as well as strategic planning for more valid research on clinical tooth preparations. A summary of the research and possible future pathways from this part of the thesis is shown in figure 8.1.

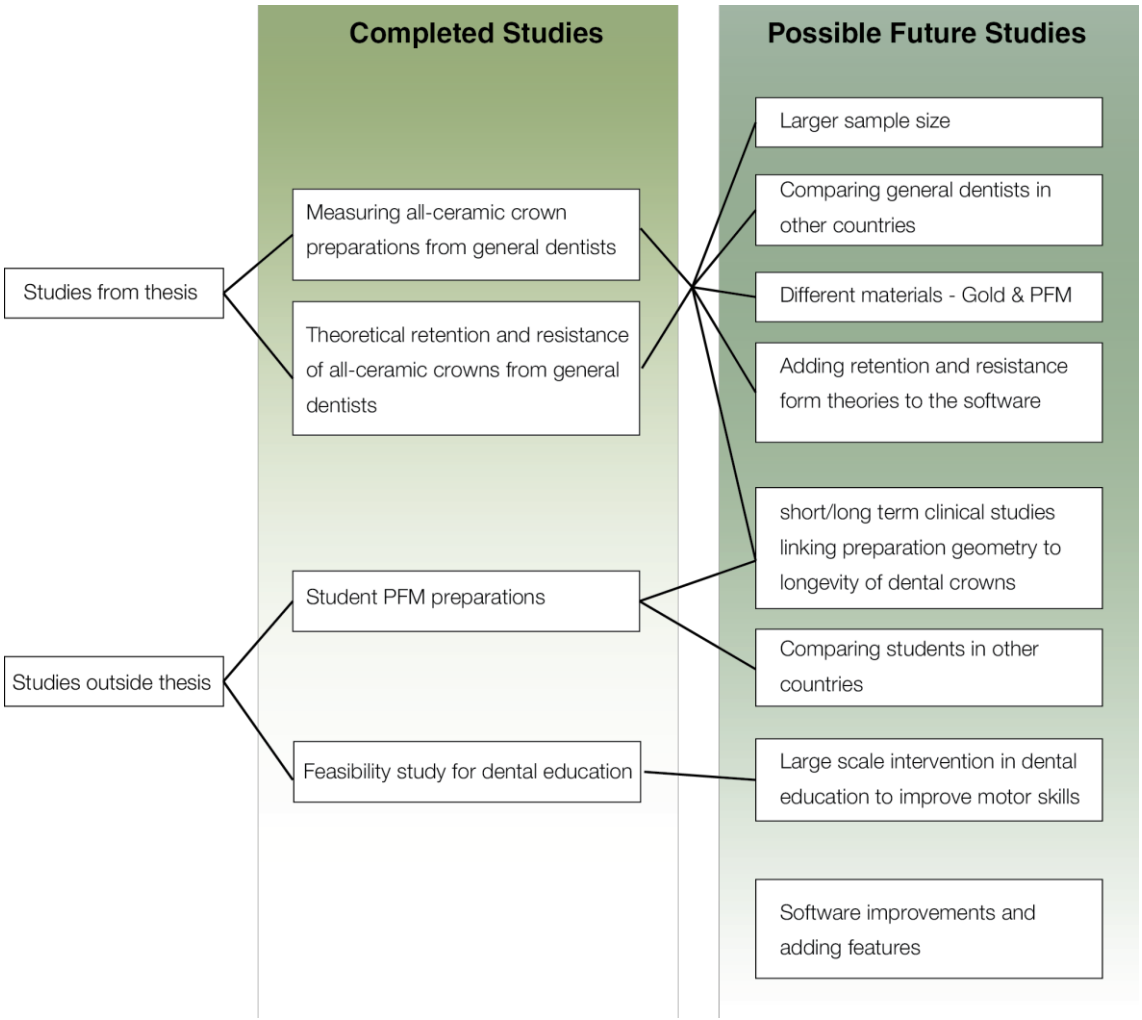


Figure 8.1 Completed studies and possible future studies

Part 2

09

Part 2 Introduction

9.1 Introduction

Measuring and recording crown preparation geometry advances our understanding regarding the intricacies of a complex system contributing to the survival of dental crowns. Part 1 of this thesis dealt with identifying the issues with existing measuring methods by introducing a new method along with a sample of measurements from general dentists. Part 2 deals with the application of this information and how we can learn and improve. Many scholars have investigated the possibility to predict clinical survivability based on crown preparation geometry (Rekow and Thompson, 2007; Rekow et al., 2007; Rekow et al., 2011). In theory, if it were possible to predict survivability, then the implications would positively affect patient outcomes and dentistry.

In reality, the crown system is reliant on a factorial amount of controlled and uncontrollable variables, thus accurate prediction of survival would be impossible (Rekow et al., 2006). However, it may be possible to take the controlled variables (such as preparation convergence angle and marginal width), understand it's individual roles on the system, and maximise its potential for clinical success (Anusavice et al., 2007).

9.2 Total occlusal convergence

The total occlusal convergence (TOC) angle is a clinician-controlled variable addressed in Part 1. The TOC is widely accepted as an important variable as manufacturers specifying recommended convergence angles for retention and resistance. The recommended value of 12 degrees convergence was founded on a compromise between early retention pull tests, and clinical achievability. Retention pull tests date back to 1955 where Jorgensen (1955) introduced his theory that maximum retention exists when the axial walls are parallel with a substantial decrease in retention after 5 degrees. Axial walls should ideally be at parallel but a little allowance is needed for practicality. This was further agreed upon by Kaufman et al. (1961), Watanabe et al. (1988), and Atta et al. (1990). Through a series of tests, the retention is modelled by the following equation:

$$retention\ \left(\frac{g}{mm^2}\right) = \frac{380}{Convergence\ angle\ (degrees)} + 5.5$$

The same experiment was repeated by Wilson & Chan (1994). The findings showed the retention peaked at a range of 6 and 12 degrees, and 25 degrees being statistically less retentive. Shekar & Giridhar (2010), found 3-6 degrees was ideal for maximum

retention, and El-Mowafy et al. (1996) compared 12 and 25 degrees and found 12 degrees performed better. Other studies also advocate for low TOC angles (Sarafianou and Kafandaris, 1997; Zidan and Ferguson, 2003).

Resistance has also been investigated using off-axis load testing. Farshad et al. (2013), found that the best way to increase retention form was to decrease the TOC angle. The theoretical models described in chapter 7 introduced the 'on or off' theory or the linear model, with both models still recommending low TOC angles (Weed and Baez, 1984; Parker et al., 1988; Parker et al., 1991; Parker et al., 1993; Wiskott et al., 1996; Wiskott et al., 1997; Cameron et al., 2006; Leong et al., 2009). TOC angles have shown to reduce resisting areas leading to poorer long-term performance (Hegdahl & Silness, 1977), and increase axial strain on the crown (Asbia et al., 2008).

It is evident that throughout the literature, low TOC angles are recommended for maximum retention and resistance. Today, the same recommendation of 12 degrees has been given to every tooth.

9.3 Failure mechanisms of ceramics

In order to understand the performance of all-ceramic crowns in terms of their preparation geometries, it is best to look at the failure mechanisms of crowns and investigate whether these can be attributed to, or be caused by geometric factors. Failure of monolithic ceramic restorations has been investigated in depth by numerous investigators (Tsai et al., 1998; Lawn et al., 2007; Rekow et al., 2009; Zhang et al., 2009) and is shown in figure 9.1.

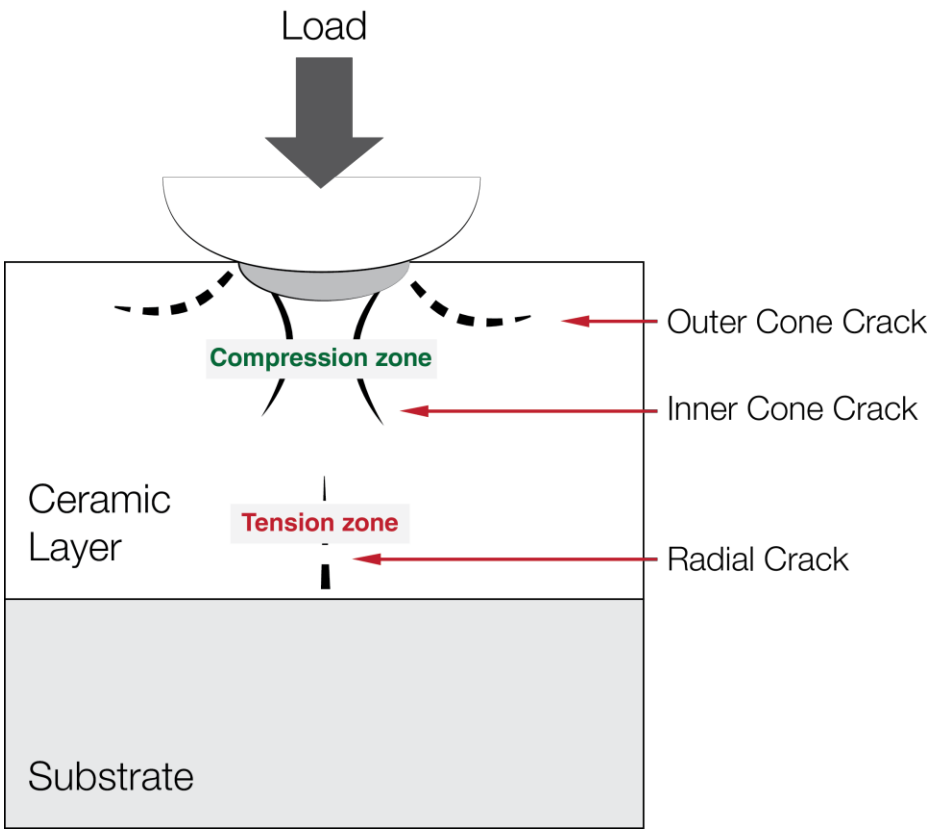


Figure 9.1 Fracture mechanisms found in *in vitro* testing of monolithic ceramics

Two types of fracture types develop in the near-field or occlusal surface. The first are the outer cone cracks, which may develop from loading but may not always propagate further. The second are called inner cone cracks, which initiate from repeated cyclic loading of the indenter and may propagate further into the specimen leading to chipping fracture.

Radial cracks develop and initiate at the cementation surface due to the tensile zone created under the applied load. These can propagate into the specimen and result in bulk fracture. This type of failure is often seen in clinically failed monolithic ceramic restorations (Kelly et al., 1989; Kelly et al., 1990).

9.4 Hoop stresses

In order to investigate the geometrical affects on the retention and resistance of a dental crown, the crown preparation and crown can be simplified to tapered cylinders as shown in figure 9.2. Simplifying the system allows specific geometric variables to be closely investigated.

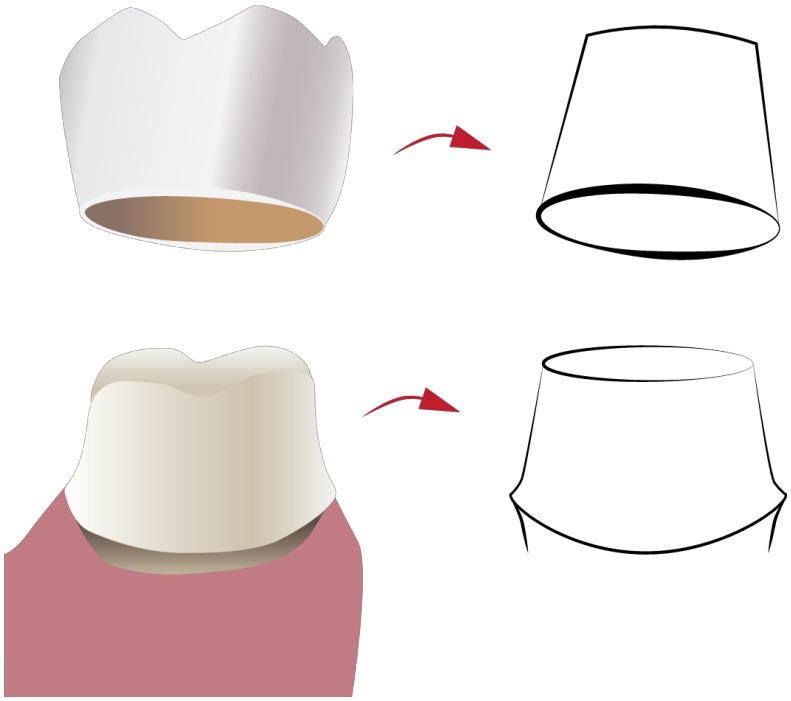


Figure 9.2 Geometrical simplifications of tooth preparation and crown

There are three principal stresses in cylinders. There are radial stress running perpendicular to the long axis, axial stress running parallel to the long axis, and hoop stress running circumferential as shown in figure 9.3.

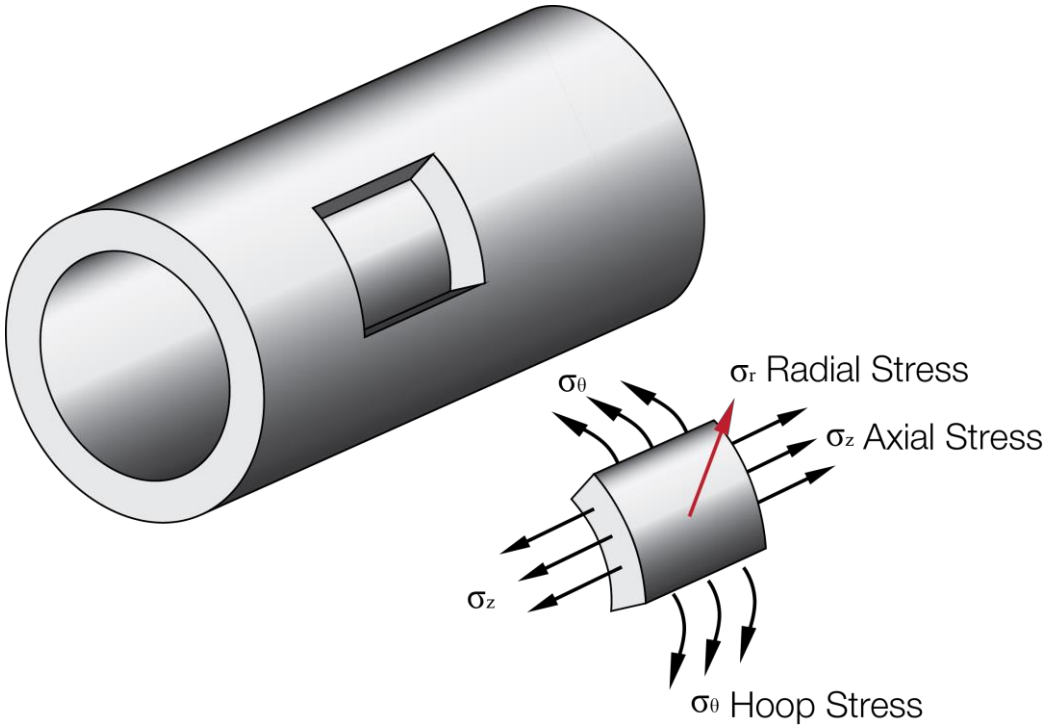


Figure 9.3 Cylinder stresses

Hoop stresses are the largest principal stress in cylinders and in the absence of other external loads, would be the cause of failures. Hoop stress is given by the following equation (Timoshenko and Woinowsky-Krieger, 1959):

(9.1)

$$\sigma_\theta = \frac{qR}{t}$$

Where σ_θ is hoop stress, q is the internal pressure, R is the radius, and t is the thickness. This is a thin-walled approximation and is based on the assumption the wall is thin (t < 10% R).

A dental crown has a larger thickness to radius ratio and can be modelled by the thick-wall assumption:

(9.2)

$$\sigma_\theta = \frac{qR^2(r_0^2 + r^2)}{r^2(R^2 - r_0^2)}$$

Where r is the radius at any given point. Maximum and minimum can then be given by the following equations:

(9.3)

$$\sigma_\theta(max) = q\left(\frac{R^2 + r_0^2}{r_0^2 - R^2}\right) \ (at\ inner\ surface\ (r = R))$$

$$\sigma_\theta(\min) = q\frac{R^2}{r_0^2}\left(\frac{r_0^2 + R^2}{r_0^2 - R^2}\right) \ (at\ external\ surface)$$

As the cylinder is axially loaded, the highest principal stresses generated are the hoop stress causing radial cracks. This crack initiates from the inner surface propagating out and growing longitudinally. As bulk fracture initiates and propagates similarly, this situation can be used to model the clinical failures (Sornsuwan and Swain 2012).

9.5 Objective

The objective for part 2 is:

1. To understand the importance of the total occlusal convergence angles by understanding their effects on fracture mechanisms and hoop stresses.

10

The influence of convergence angles on the failure of all-ceramic dental crowns

The purpose of this study is to investigate the influence of convergence angles on the fracture of all-ceramic dental crowns using in vitro, numerical, and analytical analysis. This chapter has been prepared and inserted as a manuscript.

10.1 Introduction

All-ceramic restorations are increasingly the material of choice for crowns and bridges. As such, their performance has been under much scrutiny as the key factors for survival are investigated and identified for clinical success. Crown preparation geometry is one such isolated factor that the literature has focused on (De Jager et al., 2005; Whitton et al., 2008; Rekow et al., 2009; Rafferty et al., 2010; Sornsuwan and Swain, 2011; Sornsuwan and Swain, 2012). Recognized as a clinician-controlled variable, crown preparations are also an established factor contributing to a central role influencing stress during occlusal function. Aside from technical and clinical techniques, manufacturers typically recommend measurements for minimum margin widths and a specific degree of convergence for greatest clinical performance.

The fracture mechanisms of monolithic all-ceramic systems in response to contact loading have been well documented (Lawn et al., 2004; Lawn et al., 2007). Chipping failures occur when cracks initiate near the applied load and continue to propagate, whereas clinical catastrophic failure is reported to occur as bulk fracture throughout the entire restoration (Kelly et al., 1989; Thompson et al., 1994). Far-field or radial cracks appear to initiate at the inner surface of the ceramic at the cementation interface. With continued loading, the cracks propagate through the material to the outer surface resulting in bulk fractures (Lawn et al., 2007).

Laboratory tests offer the ability to isolate a specific target variable whilst maintaining a controlled environment. This is needed to diagnose the behaviour and role of various design parameters and their influence on a model system. *In vitro* tests designed to increase our understanding in this area need to simulate clinically similar failures. Some

tests report high failure loads and different failure characteristics from what occurs clinically. For instance, local loading-induced contact failure modes still dominate *in vitro* tests in contrast to far-field radial cracks that have been reported clinically. For increased reliability, some studies employ fractographic analyses techniques to determine fracture patterns and the origins of failure observed in clinically failed crowns (Kelly et al., 1989; Scherrer et al., 2006; Borba et al., 2011). Finite element (FE) analysis has also been used in conjunction with experimental models to investigate the stress distributions and predict failure (De Jager et al., 2006; Corazza et al., 2013). These additional analyses assist with critical crack identification and possible calculation of the stresses at failure. Such information is vital when comparing the indication and contraindication of the various ceramic materials for fixed restorations.

Recently, extended finite element methods (XFEM) has been successfully been applied to fracture modelling in a range of dental prostheses (Barani et al., 2011; Barani et al., 2012; Zhang et al., 2013; Zhang et al., 2015). In contrast to another useful numerical method, namely continuum-to-discrete element method (CDEM) (Ichim et al., 2007; Ichim et al., 2007), the advantages of XFEM includes the following; it allows crack initiation and propagation from element to element without remeshing, the elements containing cracked surfaces and tips are enriched with additional degrees of freedom so the discontinuous shape function is adopted to capture the singular stress fields near the crack tip, therefore a relative accurate solution can be obtained using a coarse mesh, and the mapping of the field variables after crack propagation is not required.

The total occlusal convergence (TOC) angle is defined as the converging angle of two opposite axial walls in a given plane of a crown preparation (2005). It is recognized as the most important clinician-controlled preparation parameter (Goodacre et al., 2001; Shillingburg, 2012), with more studies measuring this parameter than any other (Tiu et al., 2014). *In vitro* studies investigating the TOC specifically have focused on retention pull tests (Jorgensen, 1955; Zidan and Ferguson, 2003; Pilo et al., 2008; Shekar et al., 2010; Madina et al., 2010), concluding small tapers (3 – 6 degrees) are recommended for maximum retention and after this point, retention is influenced by luting agent and

material choice. In terms of simulating clinical failure, TOC should be loaded to induce radial cracks leading to bulk fracture. As the largest principal cylindrical stresses, hoop stresses running circumferentially have been investigated to induce the fracture mode (Sornsuwan and Swain, 2012).

The unique combinations of geometrical parameters for a patients crown preparation present a challenge in each individual situation. Recommending the same specific measurement for only two parameters- TOC angles and margin widths, applied to every tooth in the arch still results in varied preparation designs. Which begs the questions; can the clinical success attributed to preparation design be controlled by these two parameters? How much of a role does the convergence angle contribute? And is it totally dependent or is it a parameter that is appropriate when used in conjunction with other parameters that cannot be as easily controlled? Addressing these questions brings us a step closer to understanding the intricacies of this complex system.

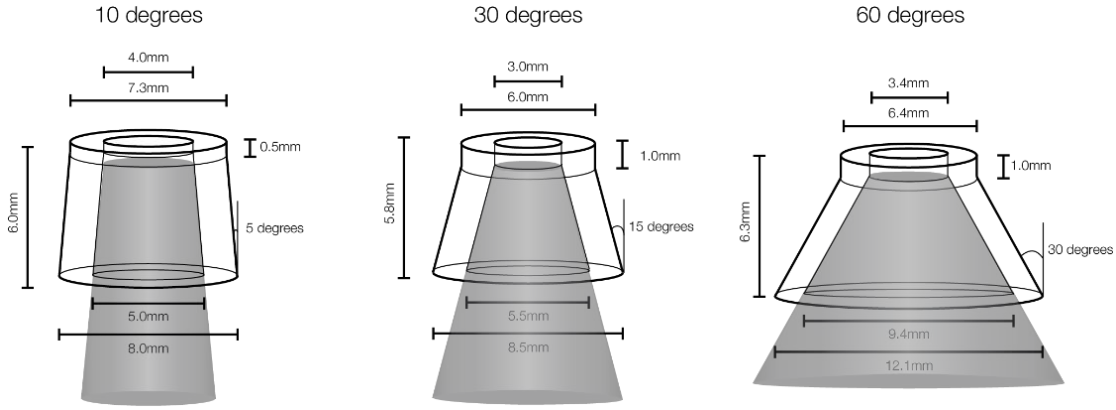
TOC is recommended by manufacturers to be 12 degrees. For retention tests, TOC values above 5 – 15 degrees is detrimental for the system, although it seems general dentists may be preparing crowns with TOC values up to 60-80 degrees TOC (Tiu et al., 2015). The aim of this study was to investigate and understand the effects of extreme convergence angles on hoop stresses and the pattern of failure in a simplified all-ceramic crown using experimental and numerical methods.

10.2 Materials and methods

10.2.1 Experimental test on glass simulated dental crowns

Ninety crown-like uncrystallised lithium silicate glass specimens (VITA Suprinity Lot 41940, VITA Zahnfabrik) were CAD designed and milled (Ceramill Map400, AmannGirrbach) with 10, 30, and 60 degrees TOC (n = 30) using dimensions as shown in figure 10.1. VITA Suprinity polishing set technical system was used to smooth the

surfaces after connectors were removed. The top and bottom surfaces were wet polished with 800 and 1200 grit sandpaper and each specimen was cleaned in an ultrasonic bath with distilled water for 10 minutes. A layer of petroleum jelly was applied on the fitting surfaces using a microbrush to reduce frictional forces between the test die and specimens.



Material Properties		
Material	VITA Suprinity (unsintered)	P-20 Plastic Mold Steel Alloy
Density (kg/m^3)	2.203	7.86
Elastic Modulus (GPa)	64-72	190-210
Poisson's ratio	0.17-0.2	0.27-0.30
Tensile Strength (MPa)	48	
Fracture Toughness (MPa.m$^{1/2}$)	0.9	

Figure 10.1 Specimen dimensions, shape and material properties

Specimens were placed on fabricated steel abutments (P-20, Emtech, University of Otago, Dunedin, NZ) with the corresponding test angles. The flexural strength (MPa) of each specimen was determined by axial compressive loading using a flat piston (INSTRON universal testing machine) to a maximum load of 500 N at a crosshead speed of 0.2 mm/min as shown in figure 10.2. Failure was identified either by a decrease in axial load or visual evidence of catastrophic failure. Specimen fragments were collected post-failure and fractographically analysed optically to identify the fracture origin and direction of crack propagation (Light microscope Nikon SMZ800

40x magnification). Force-displacement curves were reported for each group with average loads to failure (N).

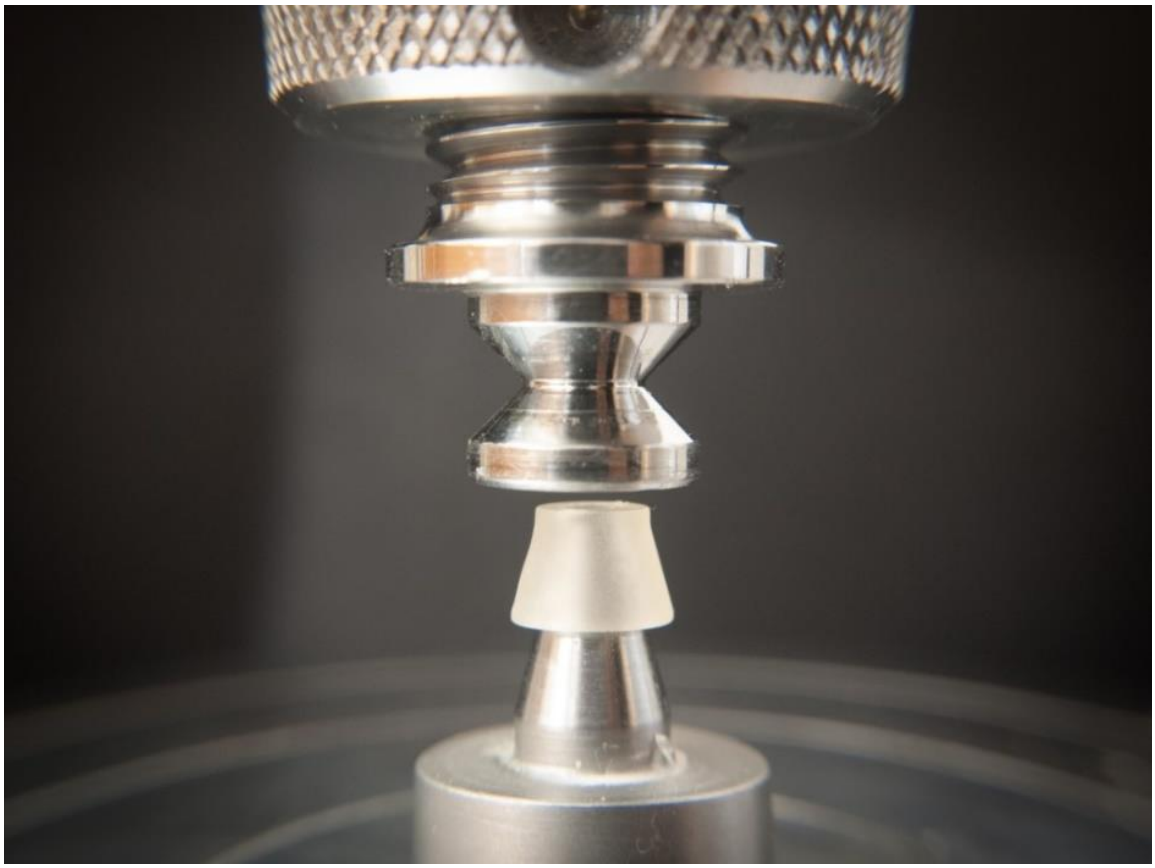


Figure 10.2 Experimental setup for loading 30 degrees ceramic crown form on a 30 degrees steel abutment.

10.2.2 Statistical analysis

Weibull distribution is recommended as a valid analysis for brittle materials and was applied to the peak axial loads (Fi). The values were calculated using the modified two-parameter Weibull equation (eq. 10.1)(Weibull, 1939):

(Eq. 10.1)

$$ln\left[ln\left(\frac{1}{1-P_f}\right)\right] = m\ lnF_i - m\ lnF_c$$

Where Pf is the probability of failure, m is the Weibull modulus or the shape parameter, and Fc is the characteristic failure load. This rearranged equation corresponds to the straight-line equation where m is the gradient. Load values were ranked from lowest to highest and given a ranked probability of failure assigned by equation 10.2:

(Eq. 10.2)

$$ln\left[ln\left(\frac{1}{1-P_f}\right)\right] = m\ lnF_i - m\ lnF_c$$

Where N is the total number of specimens, and i is the rank number (Quinn and Quinn, 2010). Means and standard deviations were calculated and significance was determined by Student T-Tests.

10.2.3 XFEM Computational modelling

Finite element (FE) models of the experiment were created (Abaqus FEA 12.0, Dassault Systemes). Glass specimen models supported by steel abutments were created as shown in figure 10.3. The TOC variable ranged from 5 degrees increasing in 5-degrees increments to 60 degrees. General surface pair contact was applied to simulate the surface interactions by assigning a frictionless contact with no bonding. All FE models were kinematically constrained on the bottom surface of the steel abutment. An axial force equivalent to a maximum load of up to 700 N was applied on the surface of the crown. All FE models were meshed using 3D 0.4 mm tetrahedral elements after a convergence test similar to a previous study (Li et al., 2004). Extended finite element method fracture analyses were performed to evaluate the formation of margin cracks.

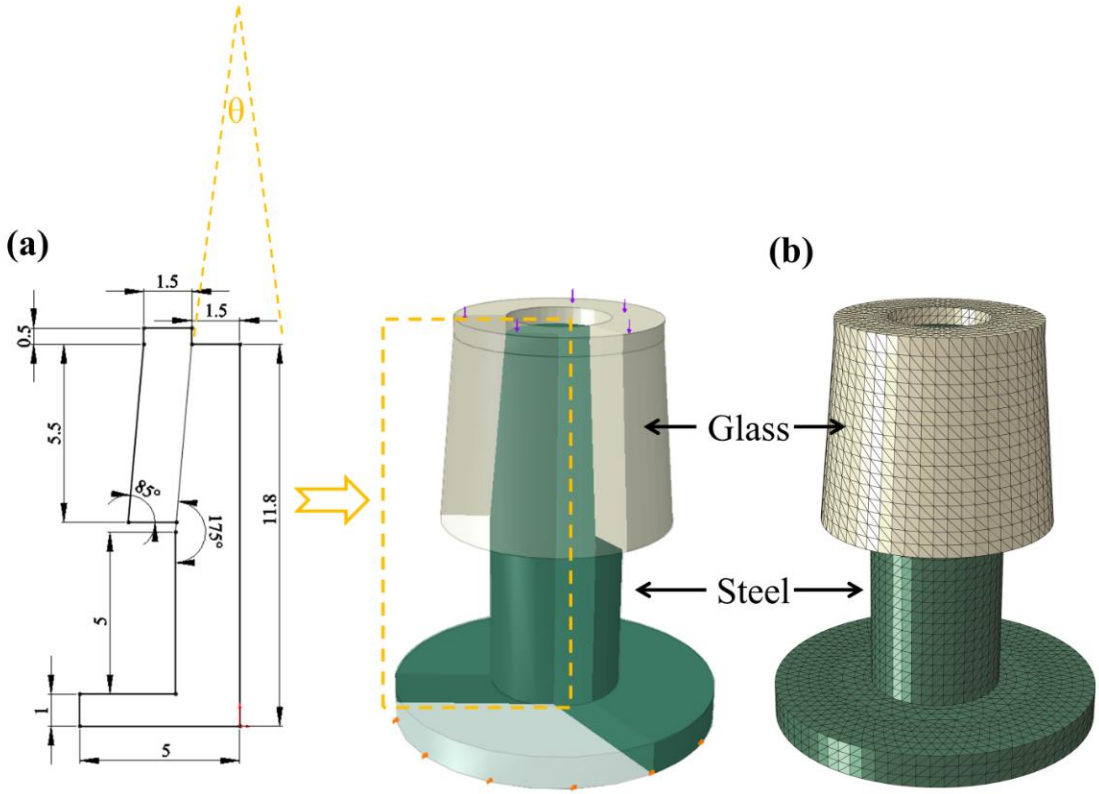


Figure 10.3 3D finite element models of glass simulated crown supported by steel abutment system (10 degrees TOC): (a) model with dimension, loading and boundary conditions; (b) FE mesh.

The material properties assigned to the models are shown in figure 10.1. The following assumptions were made in the FE model: (1) all materials were considered homogeneous and isotropic (Ichim et al., 2007; Zhang et al., 2012; Zhang et al., 2013); (2) frictionless contact was applied between the steel abutment and glass crown for simulating the non-bonded conditions; and (3) there were no significant flaws in any of the components.

Extended finite element method fracture analysis was performed to evaluate the formation of margin cracks. Damage associated with crack initiation is determined by the maximum principal stress criterion as indicated in Eq. (10.3) (Maiti & Smith, 1983).

(Eq. 10.3)

$$f^e = \frac{\sigma_1^e}{(\sigma_{max}^0)}$$

Where σ_{max}^0 represents the maximum allowable principal stress of the material (glass). σ_1^e is the maximum principal stress in element (e), while f^e indicates the stress ratio determining if cracking would occur in the element. A crack is assumed to initiate when the stress ratio reaches the value of 1(f^e = 1). Cracking takes place when the maximum principal stress within an element reaches or exceeds the predefined tensile strength of the glass material in this element. Subsequently, the crack growth is based on the strain energy release in XFEM (Giner et al., 2009). The critical strain energy release rate G (J/m^2) is a material parameter related to fracture toughness K_{1c} ($MPa \bullet m^{1/2}$), indicating the energy required to propagate unit area of a crack under mode I loading. More detailed background about the mathematics and mechanics of XFEM fracture analysis can be obtained from the literature (Mohammadi, 2008).

10.3 Results

10.3.1 Experimental results

Under the loading conditions, the specimens catastrophically failed with the majority of the 10 degree specimens fracturing in two or three pieces, while the 30 and 60 degrees specimens fractured in more than three pieces. Two specimens from the 30 degrees

group, and three specimens from the 60 degrees group were removed from the final results as they were found to be milled incorrectly. The maximum loads for each group are shown in figure 10.4a. The mean maximum load was 191.37 N (SD = 45.681) for the 10 degrees group, 202.20 N (SD = 59.658) for the 30 degrees group, and 305.80 N (SD = 92.724) for the 60 degrees group. All groups were significantly different $P<0.05$ except for the 10 degrees and 30 degrees groups. The Weibull distributions are shown in figure 10.4b. Sixty degrees TOC specimens had a larger distribution but a higher characteristic fracture load (337.63 N).

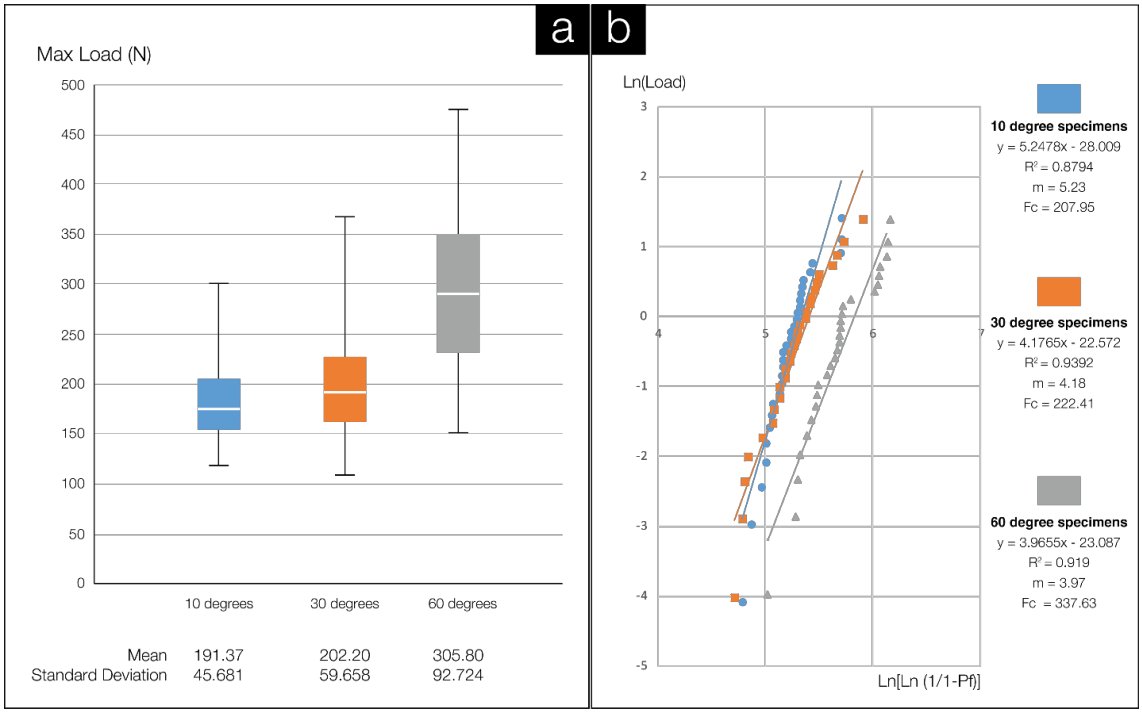


Figure 10.4 Maximum load (a) and Weibull distributions (b) for 10, 30, and 60 degrees TOC specimens, m = Weibull modulus; Fc = characteristic strength (MPa)

10.3.2 Hoop stress calculations

The loading conditions in the experimental setup result in compressive stresses developing axially while hoop stresses are generated circumferentially. The hoop stress formula used is based on a pressurized or shrink-fit cylindrical approximation. To accommodate the current situation, the formula is adjusted from a previous study (Sornsuwan and Swain, 2012). The approximation is as follows:

A steel stump is inside a tapered glass cylindrical specimen and an axial load (F) is applied (figure 10.5).

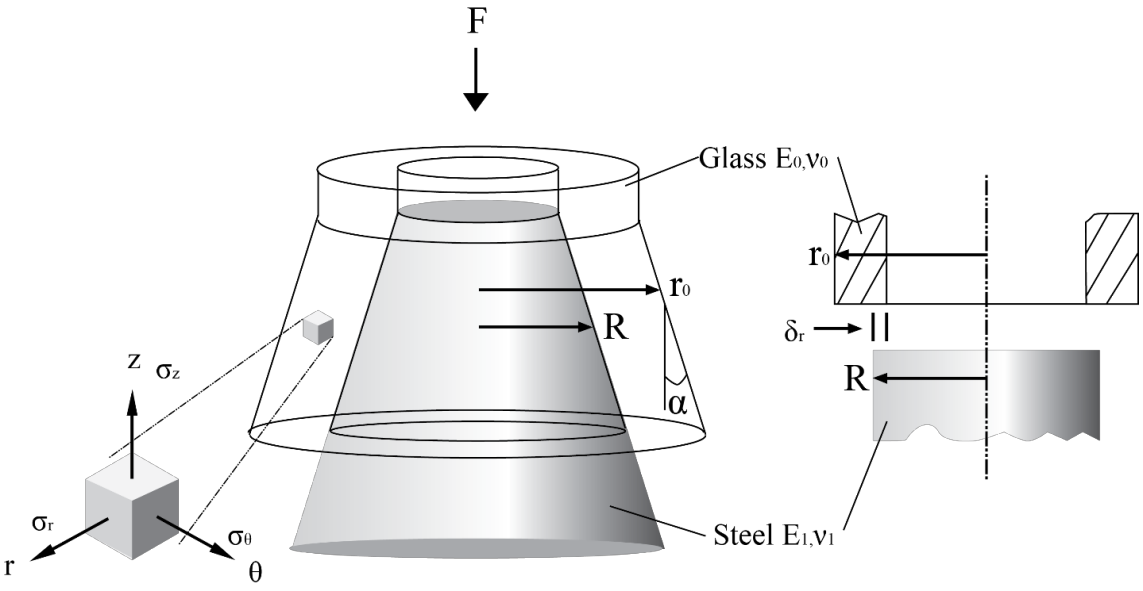


Figure 10.5 Coordinate system and definition of dimensions of the tapered steel stump inside a glass cylindrical specimen under axial load.

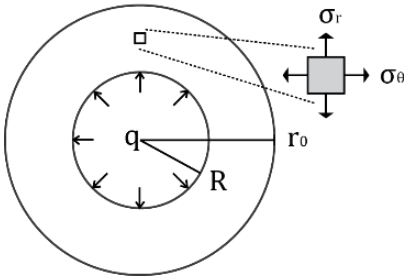
Where α is the axial wall angle in degrees, r_0 is the outer radius of glass crown in mm, R is the inner radius of glass crown in mm, F is the force exerted in N, E_0 is the elastic modulus of glass, ν_0 is Poisson's ratio of glass, E_1 is the elastic modulus of steel, ν_1 is

Poisson's ratio of steel, δ_r is the radial displacement, σ_z is the axial stresses, σ_r is the radial stresses, and σ_θ is the hoop stresses.

The situation experienced by the glass cylinder can be considered as equivalent to a pressurized or shrink-fit cylindrical shell. As the glass cylinder is loaded, axial compressive stress induces radial pressure at the steel-glass surface interface. This causes radial dilation of the tapered glass cylinder due to wedge induced radial displacement as well the Poisson effect and E modulus of the two components. As the top of the glass specimen is open ended, the upper surface of the steel stump does not experience axial (σ_z) stress, and therefore no radial displacement. Instead, the only source of pressure arises from vertical slippage in the tapered glass cylinder due to the wedging displacement.

As petroleum jelly was applied at the metal-glass interface, friction is considered low. The radial pressure developed at the edge of contact due to displacement or misfit is given by (Budynas et al., 2008):

(Eq. 10.4)



$$q = \frac{\delta_r}{R\left[\frac{1}{E_0}\left(\frac{r_0^2 + R^2}{r_0^2 - R^2} + v_0\right) + \frac{1}{E_1}(1 - v_1)\right]}$$

Where q is the internal pressure and δr is the radial displacement

As development of compressive stress at the apex of the steel stump due to axial load is minimal, the radial displacement or slippage induced misfit δ_r is related to the vertical displacement δ_z, and taper angle of axial wall α in degrees as follows:

(Eq. 10.5)

$$\delta_r = \delta_z \tan \alpha$$

10.3.3 Hoop stress

Two approximations are used to estimate the hoop stresses in the glass. A thin walled pressure vessel approximation is used when the wall thickness of the glass specimen is less than 10% of the radius. The tension within the glass is then considered uniform and is given by (Timoshenko and Woinowsky-Krieger, 1959):

(Eq. 10.6)

$$\sigma_\theta = \frac{qR}{t}$$

Where t is the thickness of the glass and σ_θ is hoop stress. In the case under consideration, the glass specimen wall thickness is greater than 10% of the radius and the thin wall approximation no longer holds. The stresses vary between internal and external surfaces and must be considered. Maximum hoop stress is generated at the inner surface and reduces towards the outer surface. The thick wall approximation for the hoop stress is given by:

(Eq. 10.7)

$$\sigma_\theta = \frac{qR^2(r_0^2 + r^2)}{r^2(R^2 - r_0^2)}$$

Where r is the radius at any given point

(Eq 10.8)

$$\sigma_\theta(max) = q\left(\frac{R^2 + r_0^2}{r_0^2 - R^2}\right) \ (at\ inner\ surface\ (r = R))$$

$$\sigma_\theta(\min) = q\frac{R^2}{r_0^2}\left(\frac{r_0^2 + R^2}{r_0^2 - R^2}\right) \ (at\ external\ surface)$$

The maximum stress at the internal surface can be determined from equations (4), (5), and (7) above, namely;

(Eq. 10.8)

$$\sigma_\theta = \frac{\delta_z \tan\alpha}{R\left[\frac{1}{E_0}\left(\left(\frac{r_0^2 + R^2}{r_0^2 - R^2}\right) + \nu_0\right) + \frac{1}{E_1}(1 - \nu_1)\right]} \cdot \left(\frac{R^2 + r_0^2}{r_0^2 - R^2}\right)$$

A consequence of the above is that the pressure q will decrease from the apex of the stump because R increases. The hoop stress dependence will be somewhat more complex as Eq(5) includes terms containing both R and r0. Another consequence is that if the strength of the glass is considered constant then for constant R + r0 the pressure q is directly related to tanα for constant δ_z The expression given by Eq. 10.8 reduces to

(Eq. 10.9)

$$\sigma = \delta_z \tan\alpha \cdot \frac{E^{\wedge}}{R}$$

Where E^ is the effective modulus considering all the ratios of inner to outer diameter and the E terms in the denominator in Eq. 10.8. E^ is calculated to be:

(Eq. 10.10)

$$E^{\wedge} = \frac{1}{\frac{1}{E_0}\left(\left(\frac{r_0^2 + R^2}{r_0^2 - R^2}\right) + \nu_0\right) + \frac{1}{E_1}(1 - \nu_1)} \cdot \left(\frac{R^2 + r_0^2}{r_0^2 - R^2}\right)$$

The problem now arises as to the determination of the displacement δz. The measured force-displacement during testing also includes deflection of the loading jig and test set-up as well as the glass cylinder displacement. That is the instrument deflection must be subtracted from the measured force-displacement results.

10.3.4 Correct estimation of displacement

Figure 10.6 shows the force-displacement curves of the raw data. The initial stages of the curves show variation where some specimens have a low initial slope before rising while others rise directly. This occurs when the top of the glass cylinder is not completely parallel with the base of the loading system. The curves were corrected by fitting a straight line to the 50N values before fracture and extrapolating back to zero as shown in figure 10.7.

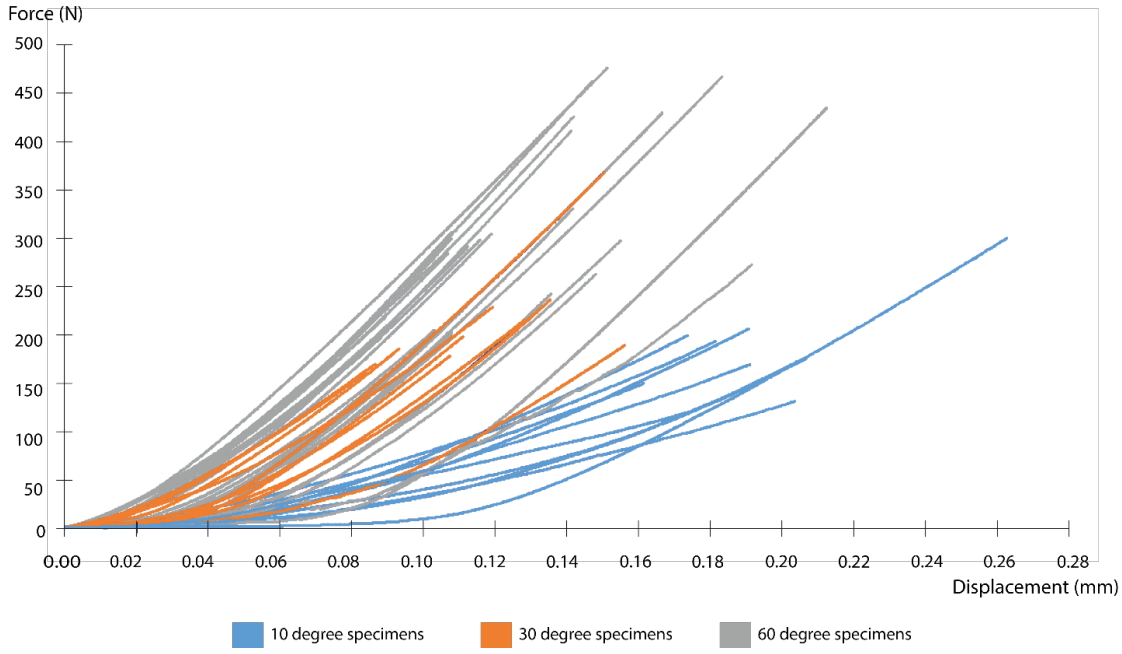


Figure 10.6 Force-displacement curves for the loading of the glass-ceramic cylinders on the steel abutments.

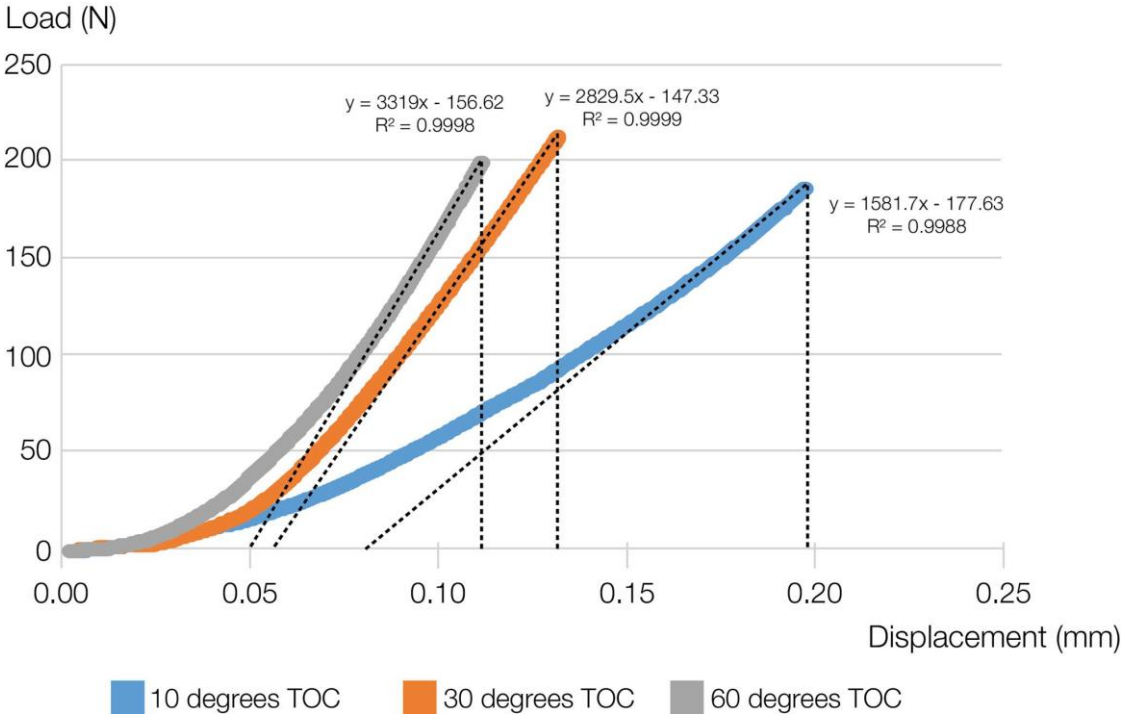


Figure 10.7 Example of straight line corrections for measured displacement

Examples from each group of fitting a straight-line equation (y = mx + c) and extrapolating till y = 0 to find displacement (δz).

To determine the machine displacement a cobalt-chrome half sphere 6 mm in diameter was axially loaded on the metal stumps, without the glass cylinder present, at a crosshead speed of 0.2 mm/min till 400N. Typical measured force-displacement curves without the glass present are shown in figure 10.8 for the 10, 30 and 60 degree TOC steel stumps. The displacement of the glass is then simply the difference between the metal stump with and without the presence of the glass cylinder. It is clearly evident from figure 10.8 that the deflection of the machine and stump occurs and is almost independent of the stump angulation. Hertz contact displacement was also calculated to correct displacement for a steel ball of 3 mm radius shown in figure 10.9.

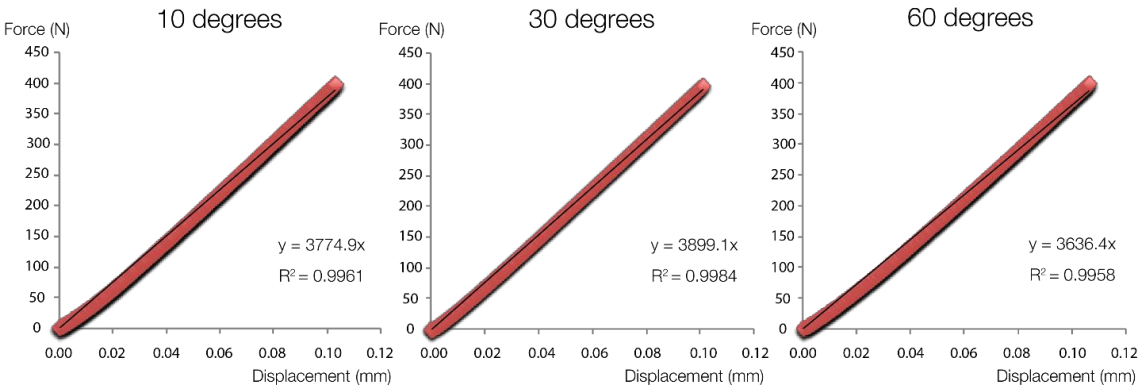


Figure 10.8 Force-displacement curves of metal stump in the absence of the glass cylinder.

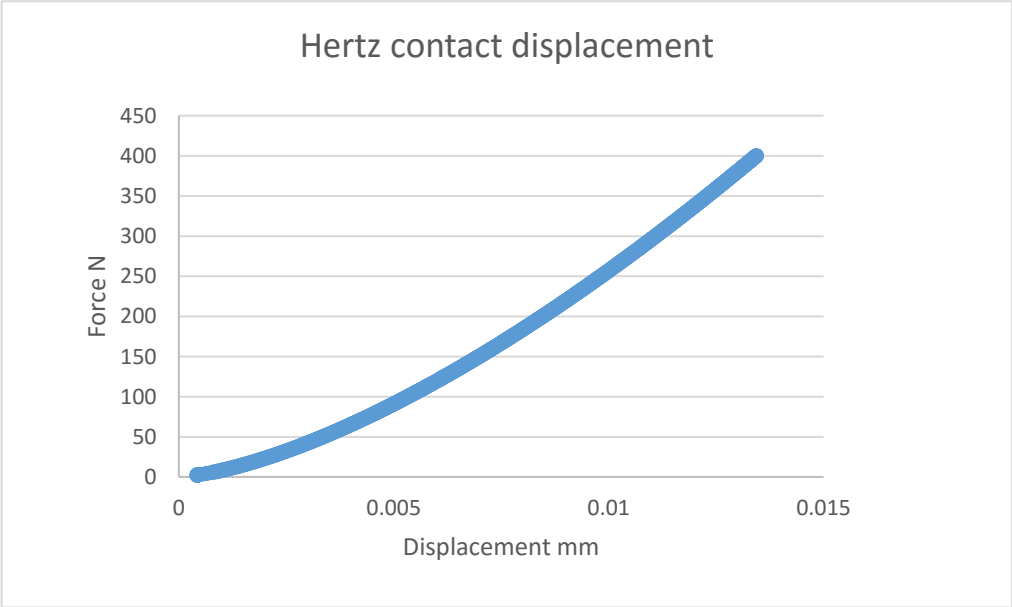


Figure 10.9 Hertz contact displacement for 3mm radius steel ball

The straight-line equations along with R2 values are shown in table 10.1 along with the load and corrected vertical displacements.

Table 10.1 Fitted straight line, R2 values, max load, displacement and corrected displacement.

TOC specimens	Fitted straight line	R value	Maximum Load (N)	Displacement δ_z after extrapolating (mm)	Displacement δ_z after Hertzian contact displacement (mm)
10 degrees TOC					
1	y = 1829.9x - 118.45	R = 0.9998	199.03	0.1088	0.0560
2	y = 1611.2x - 99.56	R = 0.9986	193.35	0.1200	0.0687
3	y = 1037x - 80.601	R = 0.9994	130.79	0.1261	0.0914
4	y = 1744.2x - 185.37	R = 0.9994	175.03	0.1004	0.0539
5	y = 1765.2x - 188.38	R = 0.9994	173.35	0.0982	0.0522
6	y = 1369.6x - 71.877	R = 0.9997	149.33	0.1090	0.0694
7	y = 1785.1x - 134.47	R = 0.9997	206.09	0.1154	0.0608
8	y = 882.5x - 34.809	R = 0.9984	119.42	0.1353	0.1037
9	y = 2257.9x - 292.85	R = 0.9999	299.58	0.1327	0.0533
10	y = 1259.7x - 72.368	R = 0.9988	169.07	0.1342	0.0894
11	y = 1759.9x - 80.704	R = 0.9999	199.56	0.1134	0.0605
12	y = 1188.8x - 65.012	R = 0.9995	153.36	0.1290	0.0883
13	y = 1127.6x - 28.53	R = 0.9999	142.83	0.1267	0.0888
14	y = 1687.2x - 83.559	R = 0.9998	204.29	0.1211	0.0669
15	y = 1784.3x - 94.491	R = 1	210.87	0.1182	0.0623
16	y = 1355.3x - 71.353	R = 0.9989	174.08	0.1284	0.0823
17	y = 2477.9x - 228.8	R = 0.9999	226.15	0.0913	0.0313
18	y = 1585.8x - 123.08	R = 0.9992	188.70	0.1190	0.0690
19	y = 1338.4x - 68.106	R = 0.9997	158.84	0.1187	0.0766
20	y = 2357.8x - 148.46	R = 0.9999	301.20	0.1277	0.0479
21	y = 1390.5x - 117.61	R = 0.9991	203.82	0.1466	0.0925
22	y = 1493.1x - 41.672	R = 0.9998	157.09	0.1052	0.0636
23	y = 1638.6x - 106.08	R = 0.9999	175.22	0.1069	0.0605
24	y = 1204.2x - 54.315	R = 0.995	179.83	0.1493	0.1017
25	y = 1338.3x - 57.504	R = 0.9998	148.60	0.1110	0.0716
26	y = 1968.8x - 152.43	R = 0.9999	209.11	0.1062	0.0508
27	y = 1803x - 116.14	R = 0.9994	230.63	0.1279	0.0668
28	y = 1581.7x - 117.63	R = 0.9988	187.99	0.1189	0.0690
19	y = 2395.7x - 127.89	R = 0.9999	300.99	0.1256	0.0459
30	y = 1344.7x - 68.123	R = 0.9995	172.87	0.1286	0.0827
30 degrees TOC					
1	y = 1784.4x - 801.46	R = 0.9947	120.31	0.0674	0.0365
2	y = 2856.6x - 1038.2	R = 1	240.26	0.0841	0.0224
3	y = 2611.5x - 1004.3	R = 0.9982	144.94	0.0555	0.0183
4	y = 1704x - 450.58	R = 0.996	122.88	0.0721	0.0406
5	y = 2829.9x - 1044	R = 0.9999	193.67	0.0684	0.0187
6	y = 2489.8x - 900.04	R = 0.9997	203.90	0.0819	0.0296
7	y = 1816.8x - 469.52	R = 0.9911	110.65	0.0609	0.0325
8	y = 3131.8x - 1192.3	R = 0.9999	278.88	0.0890	0.0175
9	y = 3388.4x - 1345.2	R = 0.9999	309.61	0.0914	0.0119
10	y = 1872.4x - 487.33	R = 0.9994	159.27	0.0846	0.0437
11	y = 2384.5x - 1043	R = 0.9994	169.22	0.0710	0.0275
12	y = 2724.8x - 1194.5	R = 0.9997	224.33	0.0823	0.0248
13	y = 1999.2x - 761.84	R = 0.9968	126.57	0.0633	0.0308
14	y = 2285.3x - 1036.1	R = 0.9993	200.48	0.0877	0.0363

15	y = 2999.4x - 1239	R = 1	289.61	0.0966	0.0222
16	y = 2393.4x - 890.76	R = 0.9998	179.20	0.0749	0.0289
17	y = 2413.4x - 1245	R = 0.9996	245.63	0.1018	0.0387
18	y = 2573.6x - 55.224	R = 0.9999	160.40	0.0623	0.0212
19	y = 3297.1x - 134.55	R = 0.9986	367.22	0.1114	0.0171
20	y = 2872.7x - 156.68	R = 0.997	235.85	0.0821	0.0216
21	y = 2753.9x - 99.941	R = 0.9999	228.07	0.0828	0.0243
22	y = 2417.7x - 188.06	R = 0.9998	189.01	0.0782	0.0297
23	y = 2950.4x - 129.29	R = 0.9999	197.52	0.0669	0.0162
24	y = 2790.9x - 121.52	R = 0.9999	177.86	0.0637	0.0181
25	y = 2919.2x - 86.509	R = 0.9999	185.48	0.0635	0.0159
26	y = 2642.6x - 58.716	R = 0.9999	169.34	0.0641	0.0206
27	y = 2829.5x - 147.33	R = 0.9999	214.91	0.0760	0.0208
28	y = 2829.2x - 127.4	R = 0.9999	216.65	0.0766	0.0210
60 degrees TOC					
1	y = 3381.7x - 229.56	R = 0.9996	241.90	0.0715	0.0050
2	y = 3319x - 156.62	R = 0.9998	201.29	0.0606	0.0053
3	y = 3429.7x - 103.92	R = 0.9998	284.11	0.0828	0.0047
4	y = 3484.9x - 85.419	R = 0.9927	303.96	0.0870	0.0033
5	y = 3355.3x - 237.77	R = 0.9999	297.08	0.0885	0.0068
6	y = 3516.5x - 209.88	R = 1	330.36	0.0939	0.0030
7	y = 3278.9x - 82.871	R = 0.9997	197.19	0.0601	0.0059
8	y = 3533.5x - 88.623	R = 1	475.27	0.1345	0.0037
9	y = 3406.1x - 147.87	R = 1	424.83	0.1247	0.0078
10	y = 3432.2x - 158.22	R = 1	410.22	0.1195	0.0066
11	y = 3239.9x - 118.48	R = 0.9998	204.95	0.0633	0.0069
12	y = 3332.9x - 129.45	R = 0.9997	151.05	0.0453	0.0037
13	y = 3401.8x - 151.01	R = 0.9999	236.93	0.0696	0.0044
14	y = 3385.5x - 103.05	R = 0.9999	227.02	0.0671	0.0046
15	y = 3438.6x - 130.78	R = 1	298.14	0.0867	0.0047
16	y = 3460.8x - 120.25	R = 1	290.36	0.0864	0.0065
17	y = 3492.1x - 201.93	R = 1	428.56	0.1227	0.0048
18	y = 3423.5x - 175.36	R = 0.9998	240.03	0.0701	0.0041
19	y = 3030.9x - 289.17	R = 0.999	272.38	0.0899	0.0149
20	y = 3507x - 230.41	R = 1	466.14	0.1329	0.0047
21	y = 3281.5x - 240.79	R = 0.9998	262.30	0.0799	0.0078
22	y = 3334.6x - 124.8	R = 0.9999	298.54	0.0895	0.0074
23	y = 3402.8x - 125.44	R = 1	303.18	0.0891	0.0057
24	y = 3542.3x - 137.8	R = 1	461.34	0.1302	0.0033
25	y = 3578.2x - 367.55	R = 1	433.70	0.1229	0.0036
26	y = 3384.9x - 123.68	R = 0.9999	297.25	0.0878	0.0060
27	y = 3199.5x - 85.436	R = 0.9999	218.44	0.0683	0.0082

10.3.5 Values of R and ro

If $R_{(outer\ base)}$ is the radius of the base, $R_{(inner\ base)}$ is the radius of the hole at the base, $R_{(outer\ top)}$ is the radius of thetop, $R_{(inner\ top)}$ is the radius of the hole at the top, h is the height of the specimen, and Y is a measured height where failure initiated, then

$$r_0 = R_{(outer\ base)} - \frac{y(R_{(outer\ base)} - R_{(inner\ base)})}{h}$$

$$R = R_{(outer\ top)} - \frac{y(R_{(outer\ top)} - R_{(inner\ top)})}{h}$$

These values were used to calculate E^ (Eq. 10.10) and hoop stress (Eq. 10.9), E0 = 70, V0 = 0.2, E1 = 200, and V1 = 0.3. The r0, R values, E^, and hoop stress for 10, 30, and 60 degrees TOC is shown in table 10.2.

Table 10.2 r0, R values, E^, and hoop stress for 10, 30 and 60 degrees TOC

Specimens	Load(N)	r0 (mm)	R (mm)	E^	Displacement δ_z	Hoop stress (MPa)
10 degrees TOC						
1	199.03	3.88	2.24	5.73E+10	0.0560	125.29
2	193.35	3.64	2.12	5.74E+10	0.0687	163.00
3	130.79	3.67	2.16	5.76E+10	0.0914	213.46
4	175.03	3.64	2.00	5.65E+10	0.0539	133.62
5	173.35	3.65	2.13	5.74E+10	0.0522	123.23
6	149.33	3.73	2.09	5.68E+10	0.0694	165.19
7	206.09	3.61	2.01	5.67E+10	0.0608	150.44
8	119.42	3.78	2.19	5.73E+10	0.1037	237.01
9	299.58	3.62	2.02	5.67E+10	0.0533	131.20
10	169.07	3.62	2.10	5.73E+10	0.0894	213.90
11	199.56	3.69	2.10	5.70E+10	0.0605	143.49
12	153.36	3.67	2.04	5.67E+10	0.0883	214.84
13	142.83	3.71	2.18	5.75E+10	0.0888	204.91
14	204.29	3.71	2.14	5.73E+10	0.0669	156.39
15	210.87	3.68	2.05	5.67E+10	0.0623	150.52
16	174.08	3.68	2.04	5.67E+10	0.0823	199.97
17	226.15	3.70	2.18	5.76E+10	0.0313	72.29
18	188.70	3.79	2.25	5.77E+10	0.0690	154.99
19	158.84	3.74	2.16	5.73E+10	0.0766	177.43
20	301.20	3.76	2.19	5.74E+10	0.0479	109.90
21	203.82	3.72	2.16	5.73E+10	0.0925	215.32
22	157.09	3.71	2.13	5.72E+10	0.0636	149.02
23	175.22	3.82	2.26	5.76E+10	0.0605	135.04
24	179.83	3.70	2.15	5.74E+10	0.1017	237.38
25	148.60	3.73	2.13	5.71E+10	0.0716	167.83
26	209.11	3.72	2.11	5.70E+10	0.0508	120.03
27	230.63	3.76	2.20	5.75E+10	0.0668	152.44
28	187.99	3.79	2.25	5.77E+10	0.0690	154.88
29	300.99	3.81	2.21	5.74E+10	0.0459	103.91
30	172.87	3.73	2.15	5.73E+10	0.0827	192.30
30 degrees TOC						
1	120.3059	3.62	2.13	5.76E+10	0.0365	264.42
2	240.2562	3.94	2.45	5.85E+10	0.0224	143.79
3	144.942	3.28	1.63	5.52E+10	0.0183	165.77
4	122.8837	3.10	1.67	5.62E+10	0.0406	366.71
5	193.6719	3.50	2.07	5.76E+10	0.0187	139.81
6	203.8997	3.58	2.05	5.71E+10	0.0296	221.15
7	110.65	3.15	1.62	5.56E+10	0.0325	298.42
8	278.8814	3.21	1.68	5.58E+10	0.0175	155.71
9	309.608	3.21	1.72	5.62E+10	0.0119	104.32
10	159.2719	3.32	1.79	5.62E+10	0.0437	368.49
11	169.2194	3.32	1.79	5.63E+10	0.0275	231.42
12	224.3315	3.22	1.72	5.61E+10	0.0248	216.81
13	126.5746	3.52	2.02	5.72E+10	0.0308	233.49
14	200.4817	3.86	2.38	5.84E+10	0.0363	238.11
15	289.6132	3.38	1.90	5.69E+10	0.0222	178.02
16	179.2022	3.71	2.22	5.78E+10	0.0289	201.64
17	245.6311	3.44	1.99	5.73E+10	0.0387	299.14

18	160.3986	3.52	2.04	5.73E+10	0.0212	159.39
19	367.2161	3.38	1.97	5.74E+10	0.0171	133.82
20	235.853	3.40	1.95	5.71E+10	0.0216	169.64
21	228.0687	2.98	1.54	5.57E+10	0.0243	235.28
22	189.007	3.41	1.85	5.64E+10	0.0297	241.55
23	197.5208	3.02	1.47	5.49E+10	0.0162	162.68
24	177.8644	3.37	1.91	5.70E+10	0.0181	144.56
25	185.4778	3.47	2.00	5.72E+10	0.0159	122.00
26	169.3413	3.42	1.98	5.73E+10	0.0206	160.02
27	214.9071	3.13	1.59	5.54E+10	0.0208	194.56
28	216.6489	3.36	1.87	5.67E+10	0.0210	170.63
60 degrees TOC						
1	241.90	3.42	2.10	5.83E+10	0.0050	79.41
2	201.29	3.45	1.97	5.71E+10	0.0053	87.79
3	284.11	3.77	2.29	5.80E+10	0.0047	68.30
4	303.96	3.55	2.10	5.77E+10	0.0033	52.74
5	297.08	3.82	2.41	5.88E+10	0.0068	95.51
6	330.36	4.76	3.35	6.08E+10	0.0030	31.94
7	197.19	3.89	2.43	5.86E+10	0.0059	81.67
8	475.27	5.44	4.12	6.25E+10	0.0037	32.74
9	424.83	5.43	4.14	6.26E+10	0.0078	68.43
10	410.22	5.31	3.94	6.20E+10	0.0066	60.44
11	204.95	3.48	1.94	5.67E+10	0.0069	115.81
12	151.05	3.50	1.97	5.69E+10	0.0037	62.48
13	236.93	3.24	1.74	5.62E+10	0.0044	83.15
14	227.02	3.51	2.12	5.80E+10	0.0046	72.33
15	298.14	4.09	2.62	5.90E+10	0.0047	60.69
16	290.36	4.53	3.07	6.01E+10	0.0065	73.49
17	428.56	3.18	1.73	5.64E+10	0.0048	90.42
18	240.03	3.72	2.30	5.84E+10	0.0041	59.56
19	272.38	3.82	2.45	5.91E+10	0.0149	207.57
20	466.14	3.67	2.08	5.70E+10	0.0047	73.57
21	262.30	3.39	1.92	5.69E+10	0.0078	132.87
22	298.54	3.62	2.19	5.80E+10	0.0074	112.83
23	303.18	5.29	3.79	6.13E+10	0.0057	52.88
24	461.34	4.30	2.78	5.92E+10	0.0033	40.59
25	433.70	3.81	2.27	5.78E+10	0.0036	52.72
26	297.25	3.45	1.90	5.65E+10	0.0060	103.53
27	218.44	2.97	1.40	5.46E+10	0.0082	183.21

After adjusting for displacement, the E^ was calculated and these values were used to calculate hoop stress as shown in figure 10.10. The mean hoop stress was 162.31 MPa (SD = 41.104) for the 10 degrees group, 204.33 MPa (SD = 68.348) for the 30 degrees group, and 82.84 MPa (SD = 40.693) for the 60 degrees group. T-tests showed significant differences between all TOC groups ($P < 0.05$).

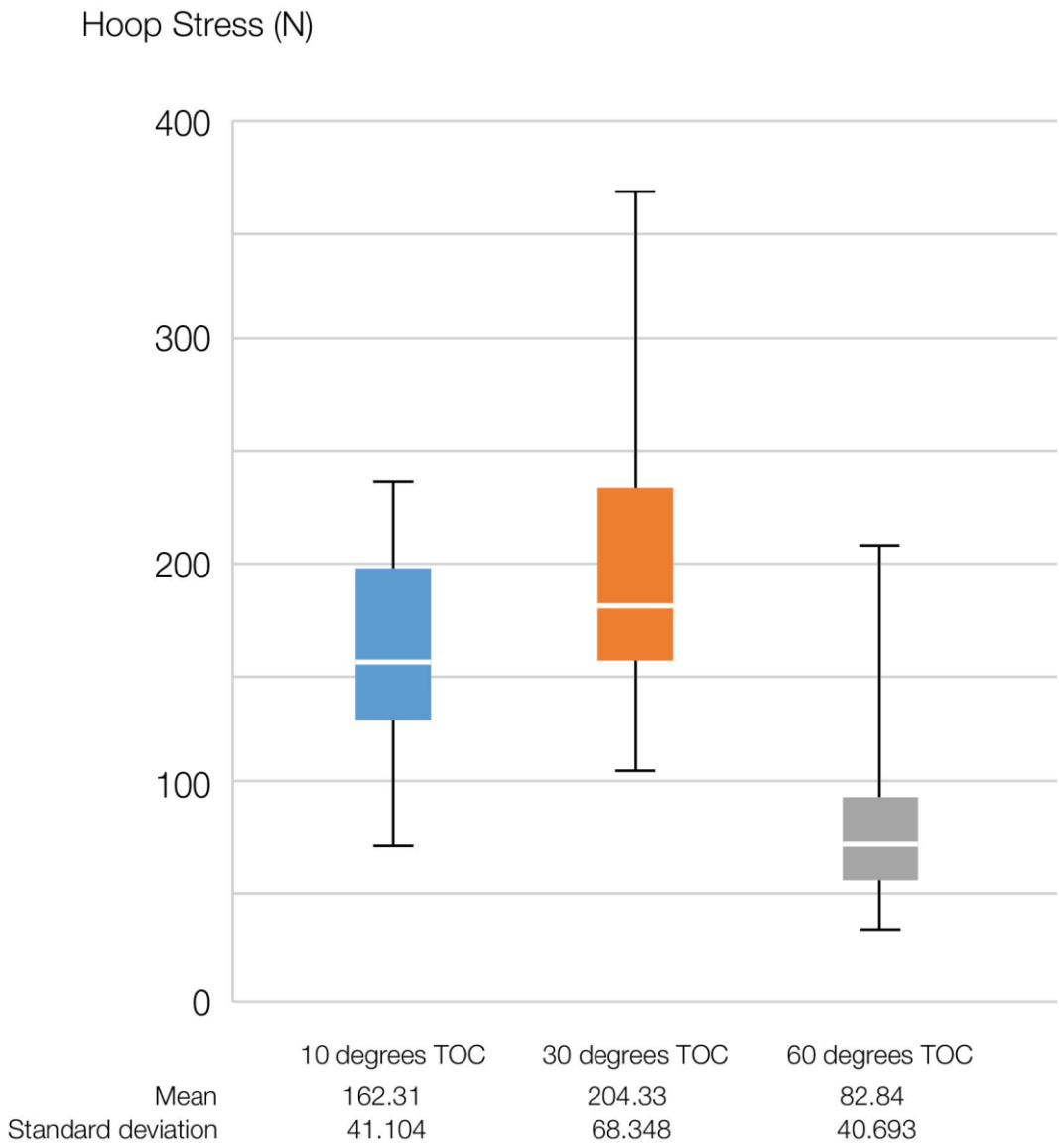


Figure 10.10 Hoop stress for 10, 30 and 60 degrees TOC specimens

10.3.6 Finite element analysis

To validate the XFEM fracture modelling of the glass ceramic simulated crown model, the force-displacement curves as well as the corresponding fracture patterns were compared with the *in vitro* experiment data. Figure 10.11a & b shows the pattern of

crack propagation observed in the experiment. Comparing the XFEM fracture analysis with the experimental results of model (the convergence angle of 10 degrees), the simulated crack initiation arose within the glass at the interface between the glass crown inner surface and steel core outer surface. On the numerical force-displacement curve (red curve) the loads for the onset of the crack initiation, its complete extension axially along the wall, and when the secondary crack initiated of the simulated crown are identified. The XFEM results exhibited reasonably good agreement with the experimental results for both the force-displacement curves and fracture patterns.

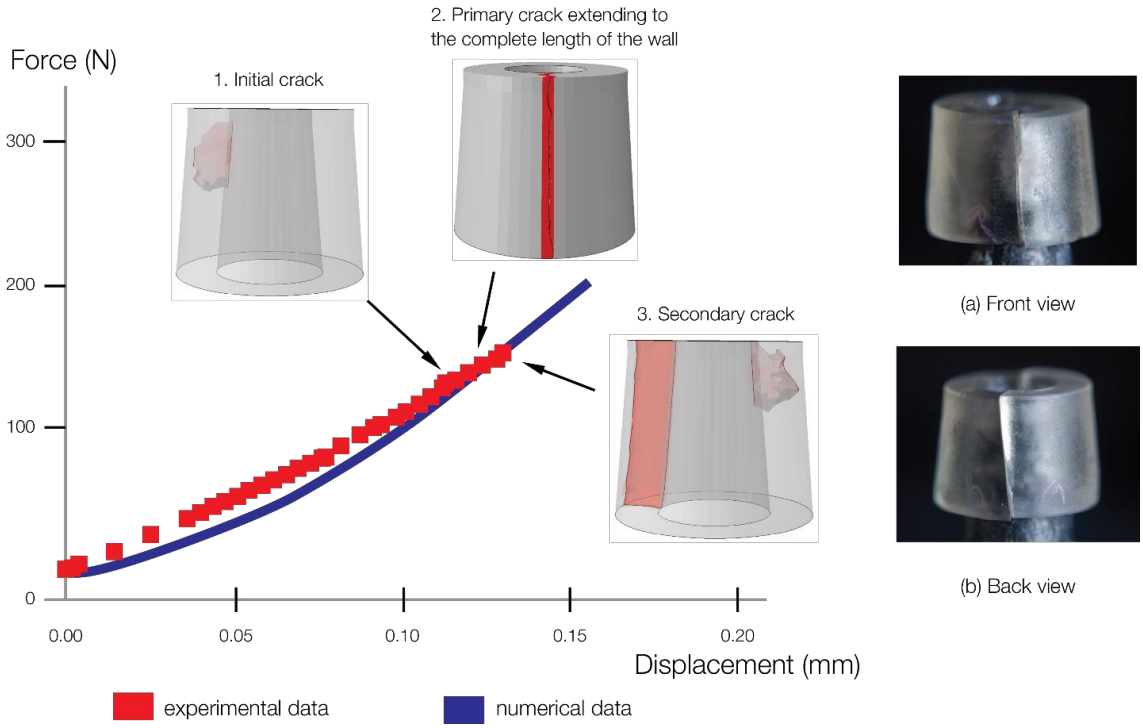


Figure 10.11 Comparison of force-displacement curves for experimental and numerical results as well as their fracture patterns of 10 degrees TOC model: (a) Cracking pattern from experiment at front view; (b) Cracking pattern from experiment at back view; (1) Initial crack started from XFEM; (2) Primary crack extended the complete length of the wall; (3) Secondary crack popped in.

Figure 10.12a shows fractographic observations of the broken specimen of a convergence angle 10 degrees model, enabling determination of the fracture origin and crack propagation directions of specimens. Crack propagation at different stages in the XFEM fracture analysis is shown in figure 10.12b. The fracture origin (O), Wallner lines (W) can be clearly seen on the fractured surface of the primary cracks with a compression curl (C) on the outer surface edge indicating the fracture initiated from the central region at the inner surface of the glass specimen, while fracture progressed to the outer surface of glass and propagated in an axial direction of the glass wall with the crack tip at the internal surface slightly ahead of that at the external surface. In the XFEM analysis, the crack initiated at the internal surface of glass crown where the highest maximum principal stresses occurred to reach the fracture strength; and then propagated to the outer surface, after that crack propagated along the axial direction downward in the glass crown.

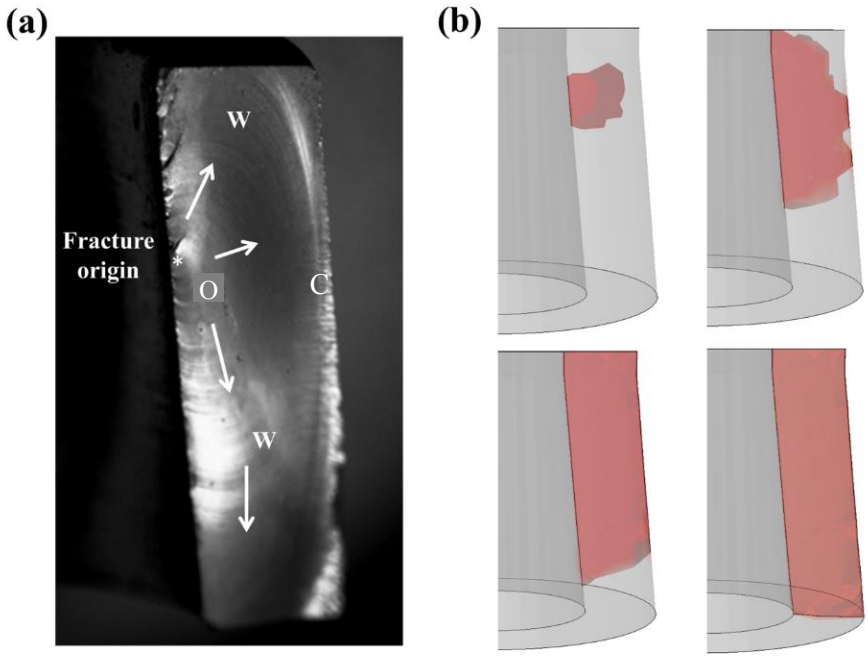


Figure 10.12 Comparison of fracture origin and crack propagation based upon the fractography and XFEM analysis: (a) primary crack from experiment test * indicates the fracture origin, W indicates the Wallner line, C indicates the compression curl, and arrow shows the direction of crack propagation); (b) fracture origin and crack propagation from XFEM.

Figure 10.13a & b shows fracture loads and the position of the crack front at different stages of crack propagation with increasing applied load. The two typical simulated fractutre patterns observed in this study displayed one fracture pattern that contained both primary and secondary cracks and another one having only the primary crack. Comparison of fracture loads for the different situations tested in convergence angle 15 and 35 degrees TOC models, the initial fracture loads when the crack initiation occurred were 195.5 N and 409.8 N, respectively. The fracture loads at which the primary crack extended close to the bottom of the glass crowns were 201.9 N for angle 15 degrees TOC model and 445.3 N for angle 35 degrees TOC model. General observations showed the primary crack extended (popped-in) and propagated as the applied load slightly increased.

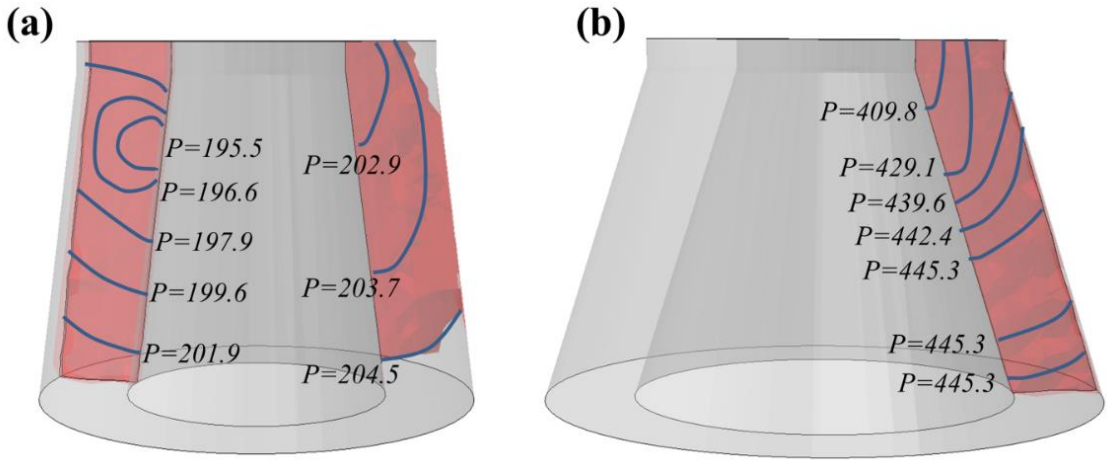


Figure 10.13 Applied loads (N) associated with crack front positions at the stages of crack propagation of two typical fracture patterns: (a) model with 15 degrees TOC; (b) model with 35 degrees TOC

Figure 10.14 exhibits the fracture loads to initiate fracture obtained from models with 5 to 60 degree TOC angles. It was found that the model with TOC angle of 60 degrees had the highest fracture load (570 N), indicating its mechanical advantage. The model with 5 degrees TOC had the lowest fracture load of 67.4 N. The fracture resistance of models increased as TOC angle increased, pr conversely, stress concentrations in the system increase with decreasing the TOC angles. From this analysis, the 60 degrees TOC model was the most suitable restoration providing the highest mechanical strength during axial loading.

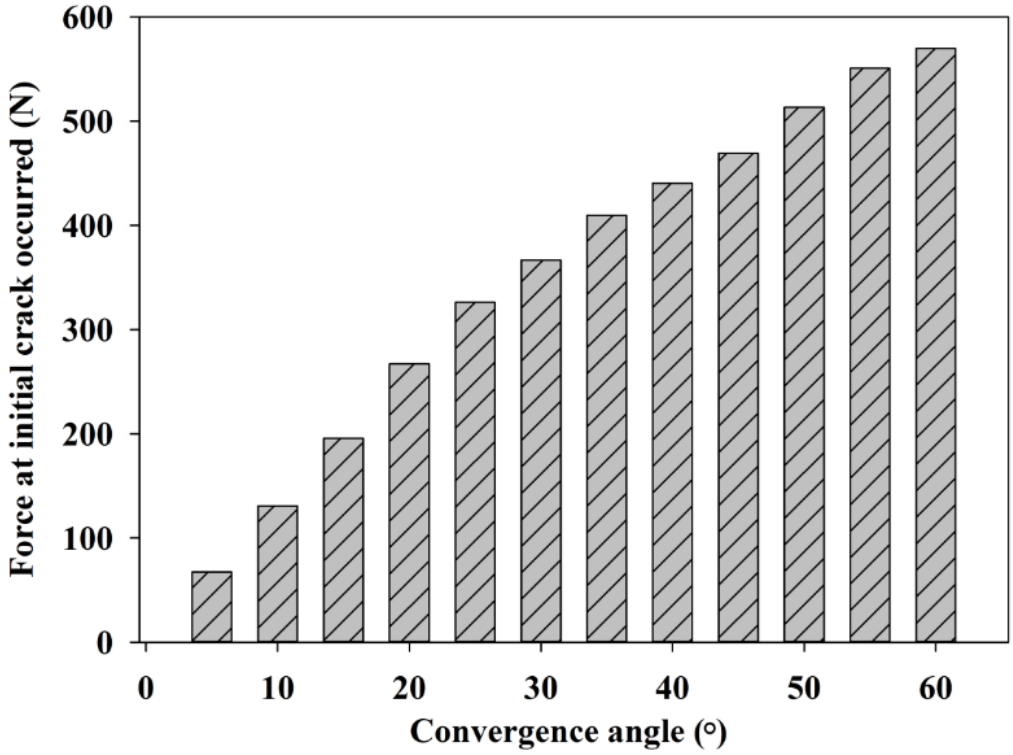


Figure 10.14 XFEM predictions of fracture loads with variation of convergence angles (5 degrees to 60 degrees TOC)

10.4 Discussion

This study aimed to investigate and understand the effects of convergence angles on hoop stresses and resultant radial fractures in a simplified all-ceramic crown model. In the *in vitro* tests, the 60 degrees TOC specimens were able to withstand statistically significant higher loads prior to failure and produced a higher characteristic strength over the 10 and 30 degrees TOC specimens. This was observed and confirmed with the XFEM model, which also showed an increase in initial crack force as the TOC angle increased.

A hoop stress approximation was used in this study. The corrected values seem to give equivalent strength values but appear to be approximately 3 to 5 times greater than expected for the uncrystallised glass ceramic (VITA Suprinity) investigated, however even with this in mind, the hoop stress values between all groups are significantly different.

This study supports the work of Rekow et al., 2009, and succeeded in reproducing hoop stress induced catastrophic failure that was initiated from radial cracks at the inner surfaces of the crowns, that then propagating outwards in a circular like manner before extending up the walls of the cylinder. This was clearly seen in the fractography performed, where fracture origins were identified on the inner surface and crack growth features were seen with the aid of Wallner lines and compression curls. These results were used to validate the XFEM models of crack growth.

The results of this study appears to favour high TOC angles for mechanical stability. In this study, the 10 degrees TOC specimens provided the least mechanical support when loaded and may result in stress concentrations in the inner surfaces of the crowns by a wedging effect. This is in contrast to the current recommended TOC angles for complete crowns in which 10 degrees is seen as an ideal angle for retention and resistance. Many studies seeking an optimum TOC angle have tested for maximum

retention and resistance. These tests may not be clinically relevant as crowns are subjected to functional loads. Traditional cemented crowns favoured very low to almost parallel convergence angles, but bonded ceramic crowns seem to be more dependent on the bonded system rather than convergence angles.

Furthermore, the high TOC angles evaluated in this study were taken from a previous study (Tiu et al., 2015) that measured the convergence angles for preparations to all-ceramic crowns prepared by general dentists. Recommendations for TOC lie within a range of 10 to 20 degrees (Shillingburg et al., 2012), yet angles greater than 20 degrees are consistently being produced. In some cases, crown preparations have been reported to be as high as 70 degrees TOC (Tiu et al., 2015). These ceramic crowns are not necessarily failing with these high angled TOC preparations although this has not been investigated. This is indicative of another factor contributing to retention, namely the bonding system. In this study however, it is evident that high TOC angles may provide more mechanical support and may in turn contribute in the crown success.

In a clinical setting, a crown preparation has many other factors such as the margin width, abutment height, and other geometrical irregularities. When combined, this makes for an intricate and complex situation. Crown material, thickness, and cement are futher factors, that can affect the clinical success of a crown. Although this complex system is not completely understood, it is important to further investigate the individual affects of each factor in a similar isolated fashion. The results from this study provide insight in the role of the TOC angles and ceramics failure mechanisms.

10.5 Conclusions

This study used a simple geometry to simulate an all-ceramic crown preparation in an experimental model and was able to reproduce clinical failure in the form of radial cracking resulting from hoop stresses. The results show large TOC angles provides greater mechanical support when axially loaded compared with the traditional

recommended low TOC angles that appear to induce stress concentrations in the brittle system by a wedging effect.

Thesis Conclusions

1 Summary of research findings

The three main objectives of the thesis were:

1. To develop a validated objective measuring method for measuring crown preparation geometry;
2. To report on the preparation geometry of tooth preparations by dentists ;
3. To understand the importance of the total occlusal convergence angles by understanding their effects on fracture mechanisms and hoop stresses.

Introductory points were given in Chapter 2 along with a brief review looking at clinical studies of all-ceramic complete crowns. This section identified the importance of tooth preparations widely accepted by the dental community to affect the retention, resistance, and survival potential of a crown. As a factor possibly affecting the survival, clinical studies fall short of providing information on these important tooth preparation parameters.

The lack of reporting tooth preparation parameters in clinical studies highlighted the need to identify the methods used to measure them. Chapter 3 presented a systematic review on studies measuring crown preparations prepared by general dentists, students, and specialists. Clinician-controlled parameters specifically focused on were the total occlusal convergence angles, the margin widths, margin angles, and abutment heights. Methods included light projection, taking photographs, sectioning dies, and digital means. The wide assortment of methods introduced subjectiveness and negated possible meta-analysis. It was evident there was a need for a universal, objective, and standardised measuring method.

Chapter 4 presented an applied mathematical in an attempt to provide an objective and standardised method theory for measuring crown preparations. Rules were presented to objectively select specific points on a crown preparation cross section. These points

were then used to calculate the preparation parameters using simple coordinate geometry. This chapter also demonstrated how this theory presented could be applied to accurately and objectively calculate and measure the following three geometric parameters in crown preparations; TOC, margin width, and abutment height.

Chapter 5 took the idea further showing the development of a program encompassing the mathematical theory. The final program (Preppr™) built upon and improved the theory presented in the previous chapter by the use of Bezier polynomials to help with objective point selection. User friendliness was upgraded with the function to upload 3D files directly to the software, the ability to adjust rotation and planes, and the output of the preparation parameters. The software demonstrated and validated its capabilities with given examples and with that, the final product completed the first objective of this thesis.

Chapter 6 demonstrated the application of Preppr™ in a large scale study. Complete crown preparations from general dental practitioners were collected and measured. Wide ranges of values were observed for TOC with average angles far greater than the recommended. Furthermore, margin widths fell short of the manufacturer recommendations of a minimum of 1 mm. This study completed the second objective of this thesis.

Chapter 7 was an extension of chapter 6. It took the geometric measurements observed from measurements of tooth preparations for all-ceramic crowns prepared by general dentists and applied retention and resistance theories to them. Further research into this area would be beneficial to investigate geometrical parameters in combination rather than investigating isolated parameters. The first part of the thesis was concluded in chapter 8.

Chapter 9 introduced part 2 of the thesis. The direction of research in this thesis changed after chapter 7 and focused on the total occlusal convergence angle in *in vitro* testing. The importance of specifying a single parameter and how it could be attributed to circumferential hoop stresses were shown.

Chapter 10 was the final study in the thesis. This multi-analysis study aimed to investigate the effects of TOC angles on the fracture of an all-ceramic crowns. Contrary to current recommendations, higher TOC angles appears to provide greater mechanical support during axial compression loads. This chapter completed the final objective of the study. Therefore all objectives were met.

Although at the present time, we may not be able to predict survivability based on crown preparation design, we can still investigate individual effects and their influence on failure. With each investigation we can move one step further and ultimately use this knowledge to improve patient outcomes.

In conclusion, this study developed a validated objective measuring method with the Preppr™ software, reported on the preparation geometry of tooth preparations by dentists, and the final study increased understanding on fracture mechanisms and hoop stresses as it relates to the total occlusal convergence angles.

2 Future research directions

This thesis has two very clear research directions.

1. The potential of the program (Preppr™) developed from this thesis lto contribute to further measuring of parameters, recording, educational training, and lead the future of digital dentistry. Digital files can be collected, measured, and kept in a centralised database where numerous questions can be asked and answered. There is an intention for the software to be distributed for further research in these hopes to potentially improve patient outcomes.
2. Part 2 of this thesis combined numerous analyses and these can be applied to more geometric parameters with different combinations. The goal is that the dental community would be able to understand and possibly predict how these

clinician-controlled parameters may affect the survivability and clinical performance of a crown.

3 Recommendations

Through the course of the work completed in this thesis, the following recommendations can be made:

1. A universally accepted standard for objectively measuring crown preparations should be established for different crown and cementation materials.

2. Studies investigating whether clinicians or students are achieving recommended values should endeavour to use an objective measuring method and report means with 95% confidence intervals.

3. Future clinical studies on the survivability of complete crowns should specify crown preparation designs to determine if these variables correlate.

4. Manufacturer recommended values for total occlusal convergence and margin widths should be revised to be more clinically achievable.

5. *In vitro* testing of crown preparation parameters should include more clinically relevant values (e.g. large convergence angles >20 degrees).

6. Studies investigating the geometrical parameters of crown preparations should focus on clinician controlled combinational parameters such as geometry and material, in *in vitro* testing to establish their importance and effect on the entire system.

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Appendix

Published abstracts

Copies of published abstracts related to the thesis are provided here. The email exchange to request reproduction is included.

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The references for the studies are:

- Tiu J, Waddell JN, Al-Amleh B, Swain MV. Capturing and Evaluation Crown Preparation Geometry. J Dent Res 92 (Spec Iss B):688, 2013 (www.iadr.org)
- Tiu J, Al-Amleh B, Waddell JN, Duncan WJ. Evaluating Clinical Molar Preparations - using the Coordinate Geometry Method. J Dent Res 93 (Spec Iss B):249, 2014 (www.iadr.org)
- Yu J, Chin E, Hung T, Tiu J, Schwass D, Al-Amleh B. Effectiveness of Dental Students' Crown Preparations using Preparations Assessment Software, J Dent Res 2015 94 (Spec Iss B)2343642, 2015 (www.iadr.org)
- Lin T, Tiu J, Al-Amleh B, Waddell JN. New Zealand Dental Students Tooth Prepparations. J Dent Res 94 (Spec Iss B):2343730, 2015 (www.iadr.org)
- Tiu J, Al-Amleh B, Zhang Z, Waddell JN, Li Q, Swain MV, Duncan WJ. Experimental and Numerical Analysis of Convergence angles in Crown Preparations. J Dent Res 2015 94 (Spec IssB):232770, 2015 (www.iadr.org)

Kind regards,

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From: Janine Tiu [mailto:janine.tiu@gmail.com]

Capturing and Evaluating Crown Preparation Geometry

Janine Tiu, Neil Waddell, Basil Al-Amleh, Michael V Swain

Introduction. Preparation affects the retention, the displacement resistance, and possible survivability of the restoration. Current methods of projecting dies and using rules are subject to human error. No universal definitions or methods exist to maintain standards and universality when collecting this information. The aim of this study is to present a novel method of capturing and evaluating crown preparation geometry.

Methods. Prepared die for all-ceramic crown was collected and trimmed by exposing the finish line. A layer of die hardener was applied. Specimen was scanned using Nobel Biocare 3D scanner. Buccolingual and mesiodistal cross sectioned images were captured. Images were exported into Engauge Digitizer 4.1 to convert into x and y coordinates. From a set of criteria, 6 selected coordinates were chosen and represented by specific labels. The points represented the largest angle differences. Using the 6 coordinates, different preparation geometry was evaluated.

Results. The total occlusal convergence angle was 27.28°. Margin angles were 144.43°, 151.34°, 99.37°, 141.27°, and widths were 0.68mm, 0.44mm, 0.44mm, and 0.53 for buccal, lingual, mesial and distal respectively. The surface area was 103.38mm . Discussion: This method is non-destructive and highly accurate. Defining criteria for selected coordinates takes out human subjectivity and standardises the procedure for selecting start and end points of axial wall convergent lines. Digitally capturing critical parameters of preparations can be integrated into systems for feedback to the dentist about the quality of preparations and for research purposes.

Conclusions. The technique is a novel method to evaluate preparation geometry and lays a strong foundation for future studies involving the consequences of each preparation parameter.

Tiu J, Waddell JN, Al-Amleh B, Swain MV. Capturing and evaluation crown preparation geometry. J Dent Res 92 (Spec Iss B):688, 2013 (www.iadr.org)

Evaluating Clinical Molar Preparations using the Coordinate Geometry Method

Janine Tiu, Basil Al-Amleh, J Neil Waddell, Warwick J Duncan

Objectives. Many studies have shown that preparations done in practice have geometric parameters that far exceed the recommended values. The important parameters are the total occlusal convergence (TOC) angle, margin width, margin angle, and the abutment height. Given the situation of an all-ceramic complete crown preparation, this study aims to compare the literature recommended values and actual preparations created in general practice using the coordinate geometry method (CGM).

Methods. 26 maxillary molar second pour preparations were collected from general practices. The samples were scanned and the buccolingual and mesiodistal cross sectioned images were captured. The image was imported into a custom program utilizing the coordinate geometry method where the geometric parameters were measured and calculated.

Results. The mean TOC angles for the 26 molars far exceeded the recommended values ($\bar{x}$=30.40 (s=9.34) > 12 degrees). The mean margin widths were below the minimum recommended values ($\bar{x}$ =0.60 < 1.00 mm), and the mean margin angles were within the recommended values ($\bar{x}$ =146.15 < 147 degrees).

Conclusions. The CGM provides a comprehensive evaluation of clinical molar preparations. The preparations provided in general practice have parameters that do not meet the minimum requirements according to the recommended values. The values using the CGM can be used in future tests to see how the shortcomings of preparations affect the performance and longevity of a crown.

Tiu J, Al-Amleh B, Waddell JN, Duncan WJ. Evaluating clinical molar preparations - using the coordinate geometry method. J Dent Res 93 (Spec Iss B):249, 2014 (www.iadr.org)

New Zealand Dental Students Crown Preparations

Janine Tiu, Tony Lin, Basil Al-Amleh, and J Neil Waddell

Introduction. Dental schools advocate for tooth preparations to be 12 degrees total occlusal convergence (TOC) and 0.5 mm margin widths for metal-ceramic crowns. This is thought to influence not only the retention and resistance, but also the potential survival of crowns. The aim of this study is to present the TOC angles and margin widths of metal-ceramic molar preparations prepared by 4th and 5th year dental students in NZ for 2014.

Methods. Forty-two digital files of student preparations for metal-ceramic molar restorations were collected for the year 2014. The files were uploaded into custom software for measuring tooth preparations. The software (Preppr™) enables the measurement of buccolingual (BL) and mesiodistal (MD) cross sections by objectively selecting 6 points to calculate TOC and margin widths using coordinate geometry. Distribution of values were analysed and presented as box and whisker plots.

Results. The TOC values for the buccolingual aspect in degrees from quartile 0 to 4 respectively are as follows; -4.28; 6.59; 15.48; 20.51; 50.82. For the mesiodistal aspect; -1.87; 18.45, 25.00; 32.64; 67.37. The combined marginal widths in mm are as follows; 0.00; 0.50; 0.74; 1.02; 2.00.

Conclusions. Students are able to achieve TOC angles close to the recommended angles for the BL cross section over the MD cross-section. However, there is a large range from negative values (undercuts) to the extreme over preparations of > 60 degrees. Majority of preparations meet the recommended marginal widths.

Lin T, Tiu J, Al-Amleh B, Waddell JN. New Zealand dental students tooth Preparations. J Dent Res 94 (Spec Iss B):2343730, 2015 (www.iadr.org)

Effectiveness of Dental Students' Crown Preparations using Preparations Assessment Software

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Objectives. The aim of this study is to evaluate the feasibility of new tooth preparation assessment software, Preppr™; as an educational tool in the learning process of attaining ideal crown preparation dimensions in an undergraduate facility.

Methods. Thirty dental students in their fourth year were randomly recruited from the student pool in February 2015 and placed in one of three groups (n=10) Group A (control group with written and pictorial instructions), Group B (tutor evaluation and feedback) and Group C (self-directed learning with aid of Preppr™). All students were asked to prepare an all-ceramic crown on the lower first molar typodont within three hours, and repeat the exercise three further times over four weeks. Industry standards of 1 mm margin widths and convergence angles between 10 to 20 degrees were taken as acceptable values.

Results. The software group had the highest percentage of students achieving minimum margin widths and acceptable TOC angles. We have also observed that those students achieved stipulated requirements earlier than other groups.

Conclusions. This pilot study's finding provide promising data on the feasibility of using Preppr™ as a self-directed educational tool for students training to prepare dental crowns.

Yu J, Chin E, Hung T, Tiu J, Schwass D, Al-Amleh B. Effectiveness of dental students' crown preparations using preparations assessment software. J Dent Res 94 (Spec Iss B):2343642, 2015 (www.iadr.org)

Experimental and Numerical Analysis of Convergence Angles in Dental Crown Preparations

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Objectives. Total occlusal convergence (TOC) angles are an important geometric parameter in tooth crown preparations. Angles as high as 60° TOC are commonly prepared by general dentists, yet studies have not investigated the effects of such high angles. The objective is to understand the mechanical effects of extreme TOC values without other influencing parameters such as marginal and occlusal support, using experimental and numerical methods.

Methods. Experimental setup consisted a compression test of precrystalized glass-ceramic non-anatomical crowns milled with 10°, 30°, and 60° TOC (n=90) on steel alloy abutments with 500N at 0.2mm/min until fracture. Numerical setup consisted of a finite element (FE) model with the same experimental dimensions meshed with 0.4mm 3D tetrahedral elements assumed homogenous and isotropic. TOC angles were tested in 5° increments from 5° to 60° and loaded in an axial direction with 700N.

Results. Experimental and numerical analysis concluded that the model with 60° TOC had the highest initial fracture load (>300N) while the lower TOC values had lower fracture loads (<190N). The extended FE results exhibited reasonably good agreement with the experimental fractographic analyses for both force-displacement curves and fracture patterns with cracks initiating at the internal surface propagating radially to the outer surface.

Conclusions. This study found a mechanical advantage with higher TOC angled restorations as they provided better support during axial loading. In contrast, the lower TOC angles that demonstrated wedging-type conditions. Nevertheless, the mechanisms are multifactorial when TOC is combined with other parameters such as margin width and will require further investigation.

Tiu J, Al-Amleh B, Zhang Z, Waddell JN, Li Q, Swain MV, Duncan WJ. Experimental and Numerical Analysis of Convergence angles in Crown Preparations. J Dent Res 2015 94 (Spec IssB):232770, 2015 (www.iadr.org)