



Fatigue and Fracture Resistance of Implant-supported Zirconia-based Hybridabutment Crowns: In-vitro Study

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Published

2017-05

Thesis Type

Thesis (PhD Doctorate)

School

School of Dentistry&Oral Hlth

DOI

[10.25904/1912/982](https://doi.org/10.25904/1912/982)

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**FATIGUE AND FRACTURE RESISTANCE OF
IMPLANT-SUPPORTED ZIRCONIA-BASED HYBRID-
ABUTMENT CROWNS: IN-VITRO STUDY**

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**Submitted in fulfilment of the requirements of the
degree of Doctor of Philosophy**

May 2017

Abstract

The current thesis is a combination of review of the literature as well as in-vitro experimental tests conducted which aimed to investigate both the fatigue and the fracture resistance of implant-supported hybrid-abutment crowns manufactured using zirconia-based material. The focus was on the following:

- **Chapter 2 (Study 1):** a systematic review of the literature for in-vitro studies which investigated zirconia-based crowns. It aimed to identify in-vitro survival rate and clarify the most clinically relevant study design to utilise in the series of experimental studies to be conducted in this thesis. After applying the inclusion criteria only 25 articles were included. Five-year cumulative survival rate of zirconia-based implant-supported crowns was lower than tooth-supported crowns (84% and 88.8% respectively). Tooth-supported crowns subjected to wet fatigue showed a lower 5-year cumulative survival rate compared to thermal cycling (62.8% and 92.6% respectively). It was concluded that survival of zirconia-based crowns depends on type of support, type of fatigue test conducted, crown structure, and veneering method. In addition, setting of standardised in-vitro fatigue testing protocols to allow for valid comparability of data was suggested.
- **Chapter 3 (Study 2):** in-vitro experiment to study the influence of using different all-ceramic restorative materials on fatigue and fracture resistance of implant-supported hybrid-abutment all-ceramic crowns. All-ceramic crowns underwent chewing simulation and static load to fracture tests and the obtained data was analysed with One-way ANOVA at a significance level of 5%. Data

analysis showed that fracture load of monolithic zirconia crowns was statistically significantly higher than that of monolithic lithium disilicate crowns. Also, exposure to chewing simulation and thermocycling has significantly reduced the fracture load in both all-ceramic materials. The study concluded that implant-supported hybrid-abutment all-ceramic monolithic crowns are capable of withstanding masticatory forces in the posterior region. Moreover, aging caused reduction in fracture resistance of the tested monolithic all-ceramic crowns.

- **Chapter 4 (Study 3):** experimental in-vitro study on the influence of using different crowns structure (mono-layer vs. bi-layer) on fatigue and fracture resistance of implant-supported zirconia-based hybrid-abutment crowns. One-way ANOVA and T-test were used to determine significance between all the tested subgroups. Upon completion of fatigue test; mono-layer crowns had 100% survival rate while bi-layer crowns had 50% survival rate. Statistics showed significantly higher fracture load of mono-layer crowns compared to bi-layer crowns. According to the results of this study, it was concluded that the structure of the implant-supported hybrid-abutment zirconia-based crown plays a major part in determining the crown's ability to resist fracture. Where mono-layer structure exhibits significantly higher fracture resistance compared to bi-layer structure. Also, resistance to fracture of the zirconia-based mono-layer structure was also affected by fatigue application and aging.
- **Chapter 5 (Study 4):** Experimental in-vitro study on the influence of using different veneering materials and different fabrication techniques (milling vs. hand-layering) on the fatigue and fracture resistance of implant-supported

zirconia-based hybrid-abutment crowns. T-test and One-way ANOVA were used to compare means and to evaluate statistical significance between all study groups. Milled crowns had 100% survival rate upon completion of the fatigue testing; while hand-layered crowns had 50% survival rate. Also, milled crowns had statistically significantly higher fracture loads compared to hand-layered crowns at baseline and after fatigue ($P \leq 0.05$). The outcome of this study showed that the veneering technique and the veneering material of implant-supported hybrid-abutment bi-layer crowns have an impact on their fracture resistance. It was concluded that milled veneers have the ability to withstand chewing forces present in the oral cavity better than conventionally hand-layered veneers. In addition, neither fatigue nor artificial aging caused any significant reduction in fracture resistant of both techniques.

Declaration

STATEMENT OF ORIGINALITY

This work has not previously been submitted for a degree or diploma in any university. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

(Signed)

PhD Candidate Name: Shareen Hayel Elshiyab

Table of Contents

Abstract.....	I
Declaration.....	IV
Table of Contents	V
List of Figures.....	VIII
List of Tables	X
List of Abbreviations	XI
Acknowledgements	XIII
Dedication.....	XIV
Published/ submitted papers included in this thesis	XV
Statement about thesis structure	XVIII
Chapter 1	2
1.1 Overview	2
1.2 Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) all-ceramic materials	3
1.2.1 CAD/CAM Glass ceramics	4
1.2.2 Polycrystalline ceramics.....	6
1.3 Zirconia in implant dentistry	10
1.3.1 Zirconia as an implant material	10
1.3.2 Zirconia as an implant-abutment material.....	11
1.3.3 Implant-supported zirconia-based restorations.....	13
1.4 Implant-supported hybrid-abutment zirconia-based crowns approach	15
1.5 Aim of the study	16
1.6 References	17
Chapter 2	37
2.1 Abstract	37
2.2 Introduction.....	38

2.3	Materials and Methods	39
2.3.1	Search strategy and study selection.....	40
2.3.2	Data extraction and survival analysis	42
2.4	Results	43
2.5	Discussion	52
2.5.1	Survival rate analysis	52
2.5.2	Fatigue testing parameters.....	55
2.6	Conclusions	59
2.7	Conflict of interest statement	60
2.8	References	61
Chapter 3		77
3.1	Abstract	77
3.2	Introduction	78
3.3	Materials and methods	80
3.3.1	Designing and milling of all-ceramic components (zirconia abutments and monolithic crowns).....	80
3.3.2	Sample preparation for testing	82
3.3.3	Assembly of study components.....	83
3.3.4	Fracture resistance testing	83
3.3.5	Scanning Electron Microscopy	85
3.3.6	Statistical analysis	85
3.4	Results	86
3.5	Discussion	88
3.6	Clinical implication	92
3.7	Limitation.....	92
3.8	Conclusions	93
3.9	Acknowledgments.....	93
3.10	References	94
Chapter 4		105
4.1	Abstract	105
4.2	Introduction	106
4.3	Materials and methods	107
4.3.1	Crowns preparation	107
4.3.2	Aging and Mechanical testing	110
4.3.3	Scanning Electron Microscopy	113
4.3.4	Statistical analysis	113

4.4	Results	113
4.4.1	Thermal cycling mechanical loading	113
4.4.2	Static load to fracture	114
4.4.3	Scanning Electron Microscopy	116
4.5	Discussion	117
4.6	Conclusions	120
4.7	Acknowledgments	121
4.8	References	122
Chapter 5		132
5.1	Abstract	132
5.2	Introduction	133
5.3	Materials and Methods	135
5.3.1	Sample preparation.....	135
5.3.2	In-vitro testing.....	139
5.3.3	Scanning Electron Microscopy (SEM).....	142
5.3.4	Statistical analysis	142
5.4	Results	143
5.4.1	Thermal cycling mechanical loading (fatigue).....	143
5.4.2	Static load to fracture (SLF).....	143
5.4.3	Scanning Electron Microscopy (SEM).....	144
5.5	Discussion	145
5.6	Conclusions	148
5.7	Acknowledgments	148
5.8	References	150
Chapter 6		158
6.1	General discussion and conclusion	158
6.2	Clinical implication	162
6.3	Limitations	162
6.4	Future recommended research	163
6.5	References	164
Appendix One.....		169
Appendix Two.....		174

List of Figures

Figure 2.1. Flow chart describing the search strategy and study selection procedure.....	41
Figure 3.1. Sintering of Zr structures in a Programat® S1.....	81
Figure 3.2. Fabrication of sample holder (A) Implant positioning and duplicating the CS sample cup to create a negative replica of the sample cup, (B & C) Creating the positive replica of the sample cup, (D) The positive sample cup replica with implant and Ti-Base.....	82
Figure 3.3. (A) A jig especially designed for SLF testing (B) Position of indenter during SLF testing.....	85
Figure 3.4. Wear facets visible on the disto-buccal cusp of tested crowns after CS (arrows) using an endodontic microscope at 12x; (A) MZr (B) MLD	86
Figure 3.5. Mean and standard deviation of fracture load in Newtons for MZr and MLD	87
Figure 3.6. Fracture path for the two tested groups after SLF (A) MZr; 3 pieces fracture along the mesiodistal plane and the lingual developmental groove (B) MLD; 2 pieces fracture along the mesiodistal plane	88
Figure 3.7. Representative SEM images after fracture resistance testing showing hackles in both (A) MZr, (B) MLD.....	88
Figure 4.1. Special jig made for static load to fracture testing to fit TCML samples	111
Figure 4.2. A) Indenter location during TCML testing (articulating paper mark on the distobuccal cusp) B) Indenter location during SLF testing.....	112
Figure 4.3. Chipping location of BLZ during TCML at the distobuccal cusp	114
Figure 4.4. Representative images of fracture path after SLF for A) MLZ crown B) BLZ crown survived TCML C) BLZ crown failed during TCML.....	116
Figure 4.5. Representative SEM images of fractured surfaces (A) BLZ fractured surface under the loading indenter at 224x showing hackles (B) pores were clear in the veneering layer at 150x (C) MLZ fractured surface at 200x showing hackles lines (D) other than remains of the ceramic material upon fracture; no pores were observed in the mono-layer crown layer at 200x	116
Figure 5.1. Hybrid-abutment used for this study; zirconia abutment (A) Ti-Base (with screw) (B) Ankylos® implant (C)	136
Figure 5.2. Fabrication of sample cup holder for fatigue testing; (A) Implants were screwed into heavy putty (Coltene whaledent, Altstätten/Switzerland) (B) Ti-Base abutment torqued to implant and ready to pour duplicate material (C) Silicone duplicate material (Exaktosil N21, Bredent) poured into the cup (D) silicone replica put to set in a pressure pot to avoid porosity (E) Silicone replica of sample cup with implant and Ti-Base abutment inverted and Acrylic resin (Palapress vario, Heraeus Kulzer Wehrheim, Germany) poured in the mold and checked in the original chewing simulation sample cup for fitting.....	140

Figure 5.3. Crowns undergoing thermal cycling in a chewing simulator during fatigue testing. 141

Figure 5.4. Position of the indenter during the compressive testing 142

Figure 5.5. Wear facets at the indenter occlusal contact upon completion of chewing simulation (arrows) (A) milled lithium disilicate veneer (B) hand-layered veneer and (C) arrow indicating the chipping on the disto-buccal cusp at the indenter occlusal contact during chewing simulation 143

Figure 5.6. Mean and standard deviation of fracture loads in Newtons (N) for all study groups 144

Figure 5.7. Representative SEM images of fractured surfaces for (A) milled lithium disilicate veneer at 250x showing hackle lines (arrows) and (B) buccal view of lithium disilicate veneer 150x, (C) view of the occlusal surface shows catastrophic chipping of the veneering porcelain (pointer) in the hand-layered veneer at 250x (D) a buccal view of the hand-layered veneer showing wake hackles as an distinctive indicator of crack propagation (black arrow) as well as pores (white arrow) 145

List of Tables

Table 2.1 Crowns type, zirconia brand used and veneering technique of the included studies..	44
Table 2.2 Life table analysis for tooth-supported vs. implant-supported zirconia-based crowns	48
Table 2.3 Life table analysis for tooth-supported zirconia-based crowns underwent wet fatigue vs. TCML	48
Table 2.4 Life table analysis for implant-supported zirconia-based crowns underwent wet fatigue vs. TCML	49
Table 2.5 Anterior vs. Posterior crowns: In-vitro life table analysis for tooth-supported zirconia-based crowns	50
Table 2.6 In-vitro experimental variables used in included studies	51
Table 2.7 In-vivo and in-vitro cumulative survival rates for zirconia-based crowns	53
Table 2.8 Thermal cycling settings adopted by the included studies	58
Table 4.1 Firing conditions for BLZ crown	109
Table 4.2 Data of failed BLZ crowns during TCML.....	114
Table 4.3 Fracture load data (N) of study groups.....	115
Table 5.1 Study components and material.....	136
Table 5.2 Firing conditions for CAD-On crowns.....	138

List of Abbreviations

CAD/CAM	Computer-Aided Design/Computer-Aided Manufacturing
Y-TZP	Yttria Stabilised Zirconia Polycrystalline
FDP	Fixed Dental Prosthesis
LTD	Low Thermal/Temperature Degradation
CTE	Coefficient of Thermal Expansion
Pf	Probability of failure
Ps	Probability of survival
Cs	Cumulative rates
AMSTAR	Assessing the Methodological Quality of Systematic Reviews
TC	Thermal Cycling
TCML	Thermal Cycling Mechanical Loading
ML	Mastication Loading
MZr	Monolithic Zirconia
MLD	Monolithic Lithium Disilicate
Zr	Zirconia
SLF	Static Load to Fracture
CS	Chewing Simulation
N	Newton
SEM	Scanning Electron Microscopy

SD	Standard Deviation
LD	Lithium Disilicate
MLZ	Mono-layer Zirconia
BLZ	Bi-layer Zirconia
HL	Hand-layer

Acknowledgements

I would like to extend the deepest debt of appreciation and thanks to my principle supervisor Associate Professor Roy George; you have been a remarkable mentor and guide for me. I would like to thank you for your ongoing encouragement throughout the years and for allowing me to grow and widen my research experience for which I have become what I am as a researcher. Without your support and guidance this research work would not have been possible. I would also like to thank my associate supervisors; Professor Andreas Öchsner and Professor Laurie Walsh for their help in sourcing the necessary equipment and facilitating resources needed to carry out this research. Moreover, I am thankful for Helen Monaghan and Kylie Mortimer; the technical support team at the prosthodontics laboratory/ Griffith's School of Dentistry and Oral Health for facilitating the use of laboratory machines, equipments, and for providing me with the necessary tools and materials needed during samples preparation stage. Furthermore, I am thankful for Ian Under hill and Chuen Lo from Griffith School of Engineering for their help in the mechanical testing.

Exceptional thanks and love to my family; mom, dad, sisters, brothers, sister in law and nieces. I can never say enough to express my gratitude for having you as my family. Your prayers for me have always kept me from tripping through hardship; it was what sustained me thus far. My sincere appreciation goes to all of my friends who helped me, put up with me and never stopped supporting me whenever I was down; you guys have made this experience pleasant. Last but not least, a tremendous thanks you to my beloved partner, who never stopped believing in me even when I stopped believing in myself through the hard times of this journey; thank you for your continuing love and for being beside me right when I needed you, you have made this experience easier.

Dedication

I dedicate this work to my family; my amazing mom, magnificent dad, beautiful sisters and supporting brothers who I have greatly missed all the past years. I also dedicate it to my beloved partner Usman for his constant support and unconditional love throughout the ups and downs of my PhD journey. I love you all dearly.

Published/ submitted papers included in this thesis

ACKNOWLEDGEMENT OF PAPERS INCLUDED IN THIS THESIS

ALL PAPERS INCLUDED ARE CO-AUTHORED

Section 9.1 of the Griffith University Code for the Responsible Conduct of Research (“Criteria for Authorship”), in accordance with Section 5 of the Australian Code for the Responsible Conduct of Research, states:

To be named as an author, a researcher must have made a substantial scholarly contribution to the creative or scholarly work that constitutes the research output, and be able to take public responsibility for at least that part of the work they contributed. Attribution of authorship depends to some extent on the discipline and publisher policies, but in all cases, authorship must be based on substantial contributions in a combination of one or more of:

- Conception and design of the research project
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- Drafting or making significant parts of the creative or scholarly work or critically revising it so as to contribute significantly to the final output.

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- Appoint one author to be the executive author to record authorship and manage correspondence about the work with the publisher and other interested parties.
- Acknowledge all those who have contributed to the research, facilities or materials but who do not qualify as authors, such as research assistants, technical staff, and advisors on cultural or community knowledge. Obtain written consent to name individuals.

Included in this thesis are papers in *Chapters 2, 3, 4 and 5* which are co-authored with other researchers. My contribution to each co-authored paper is outlined at the front of the relevant chapter. The bibliographic details (if published or accepted for publication)/status (if prepared or submitted for publication) for these papers including all authors, are:

1. Elshiyab S.H, Nawafleh N, George R. Survival and testing parameters of zirconia-based crowns under cyclic loading in an aqueous environment: A systematic review. Published in Journal of Clinical and Investigative Dentistry.
2. Elshiyab S.H, Nawafleh N, Öchsner A, George R. Fracture resistance of implant-supported monolithic crowns cemented to zirconia hybrid-abutments: zirconia-based crowns vs. lithium disilicate crowns. Accepted for publication at The Journal of Advanced Prosthodontics.
3. Elshiyab S.H, Nawafleh N, Walsh L, George, R. Fracture resistance and survival of implant-supported zirconia-based hybrid-abutment crowns: influence of aging and crown structure. Submitted for publication.
4. Elshiyab S.H, Nawafleh N, Khan U, George R. Impact of veneering technique on the survival of implant-supported zirconia-based hybrid-abutment crowns. Submitted for publication.

Appropriate acknowledgements of those who contributed to the research but did not qualify as authors are included in each paper.

(Signed)

May, 2017

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(Countersigned)



May, 2015

Supervisor: A/Prof Roy George

Statement about thesis structure

This thesis consists of six chapters: Chapter one consists of an introduction and literature review. Chapter two is a systematic review article published in the peer-reviewed journal; Journal of Clinical and Investigative Dentistry. Chapter three is an original research study accepted for publication at the Journal of Advanced Prosthodontics. Chapters four and five are also original research studies which are submitted for publication in peer-reviewed journals and currently being under the review process. The last chapter in this thesis (chapter six) is a general discussion with comprehensive discussion linking all thesis chapters. It also includes limitations of the conducted studies, conclusions and future recommendations. Bibliography of all the references will be listed at the end of each chapter.

Format of this thesis has been done in accordance with Griffith University policy on PhD thesis as published/submitted papers. As a result, there is some repetition among the papers chapters such as the description of the study design and setups.

Chapter One

Overview and literature review

Chapter 1

1.1 Overview

In prosthetic dentistry, there is a high propensity toward substituting metal-based restorations with all-ceramics' for aesthetic reasons¹. All-ceramic materials have the ability to enhance aesthetics by improving light transmission through the restorations to the body of the teeth²⁻⁴. Over the last decades, significant efforts have been made to increase strength and reliability of the available ceramic systems. Accordingly, the choice of making a full coverage crown with all-ceramic materials is increasing for additional reasons such as bio-compatibility and strength⁵.

Improvements in all-ceramic fracture strengths have gradually increased from glass-ceramic (360 MPa) to alumina (600 MPa) to zirconia (900 MPa)⁶. Both glass and alumina ceramics have good strength; but the high strength value zirconia possess⁷ has enhanced its use for high bearing load dental applications (i.e. fixed dental prosthesis (FDP), dental crowns and dental implants)^{8,9}.

Studies have showed that ceramic restorations accumulate damage during cyclic loading and thermal cycling; which weakens the ceramic restoration and can cause clinical failures¹⁰⁻¹². Single crowns composed of different materials such as lithium disilicate, leucite, and aluminium oxide have been successfully placed for 10-20 years^{13,14}. They have achieved good clinical survival rates and therefore have become the standard of care for single crowns; especially in the anterior region^{13,14}. The high veneer chipping incidence reports of all-ceramic restorations compared to that of metal-ceramic restorations have limited their use in fixed partial restorations. This could be strongly related to the location of the restoration; fracture rate in molars region have been

reported to be significantly high compared to premolars and anterior teeth (21%, 7% and 3%, respectively)¹⁵.

Zirconia¹⁶, is readily present in a monoclinic phase which is stable at room temperature. However, above 1170°C the material transforms to the tetragonal phases which will transform to a cubic phase at temperatures above 2370°C¹⁷⁻¹⁹. To stabilise the tetragonal phase, oxides such as magnesium, yttrium and calcium were added to the zirconia to make it stronger at room temperature²⁰⁻²². It was reported that yttria stabilised zirconia (Y-TZP) with a tetragonal phase can be obtained at room temperature in the ZrO₂-Y₂O₃ systems and is called tetragonal stabilised zirconia^{23,24}. This system's mechanical properties are dependent on the size of the tetragonal grains²⁵, stress applied and on the yttria content. Compared to all other all-ceramic materials, Y-TZP proved to be the strongest²⁶⁻²⁸. Further, its ability to inhibit crack propagation has made it a desirable material for use in restorative dentistry¹⁶.

This literature review will cover Advances in Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) technology in dental ceramics with specific emphasis to zirconia in implant dentistry.

1.2 Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) all-ceramic materials

CAD/CAM technology has been in use for a number of years to allow the fabrication of indirect restorations (i.e. Inlay, onlays and crowns) with minimal time. This technology uses a milling technique to process a computer-designed restoration. Ceramic materials used with CAD/CAM technology include Glass ceramics and Polycrystalline ceramics.

1.2.1 CAD/CAM Glass ceramics

1.2.1.1 *Amorphous feldspathic glass ceramics*

Vita[®] a leading company in producing CAD/CAM compatible materials were the first to develop feldspathic ceramic (Vita[®] Mark I, Vita Zahnfabrik, Bad Sackingen, Germany)²⁹ for inlay and onlays. A 10-year prospective clinical study reported a success rate for Vita Mark I inlays and onlays of 90.4%. The same study also reported the main reason for failure was ceramic fracture³⁰. High fracture rate of the ceramic was also reported after 2 years of clinical service in another study³¹. Hence, further development in materials' mechanical properties was carried out and led to the introduction of Vita[®] Mark II for CEREC (Cerec[®] I – Siemens GmbH, Bensheim, Germany)^{18,32}. This system exhibits a flexural strength of 100 MPa-160 MPa^{18,32}. The Vita[®] Mark II inlays reported higher survival rates compared to Vita Mark I of up to 10 year of clinical service^{33,34}. In line with Vita[®] Mark II, Sirona developed a feldspathic material (Cerec[®] Blocs, Sirona Dental Systems, Bensheim, Germany) which was similar to Vita feldspathic ceramic, however they offered the additional advantage of a greater range of colours and translucency. The system was only recommended for making veneers and single anterior crowns due to its inability to withstand the posterior occlusal loads⁶.

1.2.1.2 *Leucite-reinforced glass ceramics*

In 1998 Ivoclar Vivadent (Ivoclar Vivadent, Schaan, Liechtenstein) produced a leucite reinforced heat pressed ceramic (the Empress[®] ProCAD); for use with the CEREC[®] inLAB (Sirona Dental Systems, Bensheim, Germany)⁶. This material reported no fractures when used as partial crowns over a period of 4 years with high survival rate (100%) after 2 years of service³⁵. Empress[®] CAD (Ivoclar Vivadent, Schaan, Liechtenstein) was later introduced in 2006 with finer particle size and higher leucite content than Empress[®] ProCAD. This change in leucite content and particle size was to

achieve better manufacturing procedure, and to hinder damage which might occur during the machining process. The glassy matrix block in this homogenous ceramic is heat pressed to grow the leucite crystal resulting in a strong final restoration^{36,37}.

1.2.1.3 Glass-infiltrated alumina-based ceramics

Vita[®] (Vita Zahnfabrik, Bad Sackingen, Germany) initially introduced the InCeram[®] materials (InCeram[®] Alumina, InCeram[®] Spinell and InCeram[®] Zirconia) for glass-infiltrated slip-cast technique. The same materials can be made in partially sintered blocks to be milled using the CAD/CAM technology. Milled structures are then veneered with the appropriate feldspathic veneering material for anatomical characterisation³⁸. Due to the compact dry pressing of the ceramic powder into a mold while making the blocks, the amount of macro-pores is lower and more homogenous as compared to slip-casting technique³⁹. Both InCeram[®] Spinell and InCeram[®] Zirconia are modifications to InCeram[®] Alumina. Those modifications created differences in their flexural strength values (InCeram[®] Alumina 450 MPa, InCeram[®] spinell 350 MPa and InCeram[®] Zirconia 650 MPa)⁴⁰. Also, InCeram[®] Alumina is less translucent compared to InCeram[®] Spinell and is recommended for the posterior region and three unit bridges. This system has reported up to 92% survival rate when used as single crowns for restoring premolars after 5 years of clinical service⁴¹. As for InCeram[®] Spinell, it has the highest translucency among InCeram[®] systems and is recommended for use in anterior restorations⁴². InCeram[®] Spinell have a reported 100% 5-years survival rate⁴¹. Being the strongest yet the most opaque of the 3 systems⁴³; the InCeram[®] Zirconia was recommended for use as a framework for posterior crown and FDP which require only one pontic^{4,36,39}.

1.2.1.4 *Lithium disilicate glass ceramic*

Lithium disilicate reinforced ceramics (IPS e.max[®] CAD, Ivoclar-Vivadent) were introduced to the dental market in 2006 and have flexural strength of 360 MPa; which is higher than that of the leucite-reinforced ceramics⁴⁴. They were recommended for the fabrication of anterior and posterior crowns, inlays and onlays, veneers as well as implant-supported restorations⁴⁵⁻⁴⁷. The IPS e.max[®] CAD blocks are available in a pre-crystalline structure “blue state” which has a flexural strength of 130± 30 MPa. Once milled, the lithium disilicate structure is put in a ceramic furnace and goes through a crystallisation process. This process increases the material’s strength to 360 MPa^{48,49} and gives it the selected colour and translucency⁵⁰. Compared to Empress[®] CAD systems the lithium disilicate e.max[®] CAD system showed superior fracture load than both of the aforementioned systems⁵¹.

Clinical and experimental studies have shown good survival rate and resistance to fatigue for lithium disilicate crowns. Guess et al (2010) reported that monolithic e.max[®] CAD crowns were resistant to fatigue during cyclic loading in laboratory simulation⁵². Also, short-term clinical studies on lithium disilicate restorations showed survival rates between 97.4%⁵³, and 100% after two years of clinical service when used as a single crown⁴⁹.

1.2.2 Polycrystalline ceramics

The gradual addition of crystalline material content and the reduction of glass content in ceramic restorative materials led to the development of a material with glass-free microstructure. The crystals in these microstructures are densely sintered together and packed in regular arrays; which results in a strong and tough structure with low potential of crack compared to the irregular glass ceramics⁵⁴. Processing of polycrystalline ceramics is difficult compared to glass ceramics. Hence, it was the

availability of CAD/CAM technology that made it possible to fabricate frameworks from alumina and zirconia polycrystalline ceramics⁴².

1.2.2.1 Alumina

Procera[®] AllCeram alumina (Nobel Biocare, Goteborg, Sweden) was the first dental polycrystalline ceramic³⁶. It contains more than 99.9% alumina and has a flexural strength of almost 600 MPa⁵⁵⁻⁵⁷. Fabrication of the alumina crown involves milling of an enlarged die duplicate followed by densely packing aluminium oxide on the die followed by sintering⁵⁷. Once sintered, the coping is then veneered with the compatible low fusing veneering porcelain to achieve aesthetics⁵⁷.

Although the polycrystalline structure is relatively opaque, they provide comparable aesthetics to Empress[®] systems (Ivoclar-Vivadent, Schaan, Liechtenstein) when manufactured to the recommended veneer thickness³. In addition, when used as anterior and posterior crowns, the Procera[®] AllCeram reported clinical cumulative survival rates of about 97% after 5 years and 93.5% after 10 years^{58,59}. However, high fracture rate of crowns was reported in molars compared to premolars⁵⁹⁻⁶¹.

1.2.2.2 Zirconia

Procera[®] AllCeram Alumina was mainly fabricated as a framework for single crowns and dental implant abutments^{58,62,63}. Reports suggested that they had a risk of fracture during both laboratory work and in clinical use^{60,64}. These limitations led to the development of zirconia polycrystalline ceramics. There are three types of zirconia polycrystalline ceramics used in dentistry; 1) Magnesium partially stabilised zirconia, 2) Ceria stabilised zirconia/alumina nanocomposite (Ce-TZP/A) and 3) Yttria partially stabilised tetragonal zirconia polycrystals (Y-TZP)⁶. The first is stabilised by magnesia and has a high wear rate and low mechanical properties compared to the Y-TZP^{16,65}; which limits its use in dentistry. Ceria stabilised zirconia/alumina nanocomposite (Ce-

TZP/A ceramics are resistant to low thermal/temperature degradation (LTD); however, they have reported low flexural strength⁶⁶. Ce-TZP/A is reported to be reliable when used as framework material for posterior FDPs⁶⁷. Of all the three form of compatible zirconia used in dentistry, the Y-TZP is the most widely used^{6,17} because of its reported higher flexural strength (900 to 1200 MPa)⁶⁸.

Y-TZP restorations can be processed either by: hot isostatic pressing (HIPed)⁶⁹ or what's so called hard milling¹⁹; or soft milling. In the hard milling, the frameworks are machined from a highly dense sintered prefabricated zirconia blanks (fully sintered with full strength) zirconia blocks, to their final designed dimensions⁷⁰. However, with soft milling (non-HIPed) enlarged frameworks are machined out of partially sintered zirconia blanks (green-state zirconia) and then sintered to their full strength. The sintering process is associated with shrinkage rate of almost 25% to the desired dimensions⁷¹. Hard milling technique provides superior marginal fit because no shrinkage is involved in their manufacturing process; a marginal misfit of a restoration provides good environment for plaque accumulation and subsequently periodontal diseases⁷². However, both HIPed and non-HIPed materials are considered clinically alike⁷³. Examples of soft milling systems are Lava Zirconia (3M/ESPE, USA), Procera Zirconia (Nobel Biocare, Sweden), Cercon (Dentsply, USA), IPS e.max[®] ZirCAD (Ivoclar Vivadent, Schaan, Liechtenstein), Zenostar (Ivoclar Vivadent, Schaan, Liechtenstein). In addition, Denzir (Cadesthetics AB, Sweden) and KaVo Everest (BIO ZH Blank, KaVo Dental, Germany) are examples of systems adopting hard Machining.

Y-TZP has been widely used in dentistry as posts, crowns, FDPs, orthodontic brackets, implants and implant abutments^{6,7,74,75}. Studies have reported that fracture of the connectors was the main mode of failure in FDPs^{76,77}. This fracture is initiated at the gingival embrasure and can be reduced by creating a connector designed with more

gingival embrasure curvature^{78,79}. As for zirconia frameworks, they have strength which is three times higher compared to other all-ceramic materials and can withstand masticatory forces applied in the molars region^{77,80,81}. Fracture of zirconia frameworks is rarely reported^{79,82}; yet fracture of the veneering ceramic has been reported as 20% after 5 years follow-up⁷⁷. It is considered a major drawback in zirconia-based restorations and causing factors are being studied. Factors such as existing stresses or deformation during the veneering process⁸³, limitations of the veneer material and the core/veneer bond⁸⁴ and framework design^{85,86} might be the causes of veneer chipping. Moreover, resulting residual stresses from the mismatch in the coefficient of thermal expansion (CTE) between the framework and the veneering material or rapid cooling process after heat treatment⁸⁷, might be the cause of veneer chipping as well.

When compared to other ceramics Y-TZP ceramic exhibits superior flexural strength as well as high resistance to wear and corrosion^{16,17,88}. Nonetheless, factors such as stress and temperature can affect the mechanical properties of zirconia, by initiating its crystalline phase transformation from tetragonal to monoclinic.

1.2.2.3 Mechanical properties of zirconia

Zirconia ceramics are known to have a transformation toughening phenomenon. Where under a mechanical stress at crack tips, transformation from the tetragonal to the more stable monoclinic phase occurs and it is associated with volumetric expansion²². This volumetric expansion compresses the crack tips together and stops the crack propagation and thus opposing the tensile force; improving the mechanical strength and toughness of zirconia ceramics²². However, zirconia strength is dependent on its grain size²⁵; where the transformation toughening phenomenon occurs above a critical grain size of $>1 \mu\text{m}$ ⁸⁹. This phenomenon would not occur if the grain size of zirconia was less than $0.2 \mu\text{m}$ ^{25,90}.

Different to all other ceramic materials, zirconia may go through LTD or so called “Aging”⁸⁸. It is considered as mechanical property degradation in zirconia that occurs in the presence of water and water vapour and is faster at elevated temperatures^{91,92}. Hence, it is essential to maintain the tetragonal phase at room temperature; to avoid the progressive and spontaneous transformation from tetragonal to monoclinic phase at the relatively low temperatures^{93,94}. Such transformation starts on the zirconia isolated grain surface and leads to an increase in crystals volume, during which macro and/or micro-cracks might appear⁹⁴ and water is able to penetrate and the process continues^{19,91,95}. This eventually results in reduction of both fracture strength and toughness causing remarkable decrease in strength^{93,94}. This strength degradation is related to factors such as stabiliser’s content, its grain size and distribution¹⁶ as well as the existence of residual stresses⁹⁶.

Reduction of the mechanical properties of zirconia was found to be within clinically acceptable limits in simulated dental treatment conditions⁸¹. However, its vulnerability to aging has made it of high concern to the dental community and resulted in a large number of studies to determine the extent of this aging phenomenon and its implications on the long-term success of dental restorations.

1.3 Zirconia in implant dentistry

1.3.1 Zirconia as an implant material

The use of titanium and titanium alloys as a dental implant material has proved to be successful over the past years^{97,98}. However, concerns of toxicity reactions to metals, the biological issue of the relatively high metallic wear particles as well as aesthetic tooth-like colour favourability, have increased the demand toward a ceramic material that could serve as an implant⁹⁹⁻¹⁰¹. Hence, zirconia dental implants have surfaced in 2008¹⁰²

as an alternative dental implants material; having the ability to osseointegrate¹⁰³ and being of a tooth-like colour¹⁰⁴.

Strength studies showed that Y-TZP implant possess sufficient strength to survive mastication loads which the dental implants undergo¹⁰⁵. Also, conducted in-vitro biocompatibility tests have shown no cytotoxic effect of Y-TZP implants on any of the surrounding tissues^{106,107}. Moreover, in-vivo studies reported comparable soft tissue response of both titanium implants and zirconia implants when used in-situ^{108,109}. Furthermore, bacterial adhesion to zirconia was almost similar or even less to that of titanium^{108,110}.

The previously mentioned findings have led to the possibility of utilising zirconia polycrystalline for manufacturing implant abutments which need to have low potential of bacterial adhesion and provide the required aesthetic at the same time.

1.3.2 Zirconia as an implant-abutment material

Implant abutment is the component located between the dental implant and the implant-supported restoration/crown. It can be pre-fabricated by the manufacturing company, or custom made^{102,111} in the dental laboratory by the technician or by using the CAD/CAM technique¹¹¹. While the pre-fabricated abutments offer convenience and are readily available to utilise, a better successful clinical outcome is achieved when utilising the custom made abutment. Custom abutments can accommodate the various clinical complications, provide better soft tissue support and create better aesthetics¹⁰².

Titanium alloy abutments have reported high clinical success and accordingly were considered the gold standard for custom implant abutments¹¹². Nevertheless, these alloys tend to create greyish discolouration when placed under the soft tissue making them an un-aesthetic choice especially in the anterior teeth¹¹³. Hence, the enforcement

of all-ceramic abutments has been needed. The developments of the high strength and biocompatible Y-TZP accompanied with CAD/CAM technology have made it feasible for use as a customised abutment material.

Zirconia abutments are reported to provide good biological responses that are similar to those reported for titanium abutments^{114,115}. Zirconia was first used as a custom abutment material by Glauser et al in 2004¹¹⁶. This abutment was reported to provide sufficient stability as well as good soft and hard tissue response when used in both the anterior and premolars region¹¹⁶. In a separate clinical study, patients reported no swelling, pain or discomfort throughout the 3-years period of the study¹¹⁷. Also, neither zirconia abutment failure nor restoration fracture was observed¹¹⁷. In addition, zirconia and titanium abutments were evaluated in a randomised controlled clinical study¹¹⁸, and reported similar survival results after 3-years of oral function; as well as comparable biological outcome. Moreover, 11-years follow-up study on zirconia abutments placed on Noble Biocare implants showed abutment cumulative success rates of 96.3%¹¹⁹. Furthermore, zirconia customised abutments have also performed well in a recent study with 10-11 years follow-up¹²⁰.

A systematic review that aimed to evaluate and compare the 5-year survival rate of zirconia abutment vs. titanium abutment reported similar survival rates when both abutment materials were used¹²¹. Other systematic reviews revealed that zirconia abutments are able to function without fractures during 3-5 years when used in anterior and posterior regions⁷⁴. In addition, the measured colour response of peri-implant mucosa showed better aesthetic outcome when zirconia abutment were used¹¹³. A more recent systematic review by Zembic et al (2014) reported that after a long service of 11-years none of the restorations supported by the zirconia abutments fractured¹²².

Nevertheless, careful handling procedures are essential to avoid possible fracture while tightening of the zirconia abutments¹²³.

1.3.3 Implant-supported zirconia-based restorations

Indications of implants use have expanded to include implant-supported restorations for partially edentulous arches and have proven to be potentially successful treatment^{124,125}. Such successful treatments have encouraged the dental practice to give rise for implant-supported single-tooth restorations¹²⁶; which can be challenging for a clinician^{127,128}. Treatment success in such cases does not only depend on the successful osseointegration and the implant's functional load-bearing capacity, but also on the harmonious integration of the crown into the dental arch¹²⁹⁻¹³¹.

Encouraging in-vivo and in-vitro mechanical behaviours of zirconium oxide (ZrO₂) based restorations have led to their increased use over the last decade¹³²⁻¹³⁵. Being a polycrystalline material, zirconia-based ceramics are relatively opaque in nature and require a layering ceramic to be veneered to provide the desired aesthetics⁴².

Systematic reviews reported different chipping rate of zirconia-based all-ceramic crowns when supported by implants. Jung et al reported similar 5-year cumulative veneering failure rate of 3.5% for both all-ceramic and metal-ceramic implant-supported single restorations¹⁰⁰. In addition, 3% ceramic chipping was reported for zirconia-based restorations supported by implants in other systematic reviews^{132,135}.

Comparing tooth-supported to implant-supported zirconia-based bi-layer restorations, Larsson and Wennerberg¹³⁶ review reported 5-years cumulative survival rate of 97.1% for implant-supported crowns compared to 95.9% for tooth-supported crowns. They have also reported veneer chipping as the main cause of failure in the zirconia-based implant-supported restorations compared to the tooth-supported restorations (78% and

23% respectively). In addition, a 5-year survival probability of 98.3% was reported for zirconia-based implant-supported crowns with veneer chipping (8.2%) also being the most common reason for failure¹³⁷. Implant-supported zirconia-based restorations have more technical complications and veneering material fracture compared to tooth-supported restorations^{132,136}. The cause for such differences is maybe due to the presence of the resilient periodontal ligament on the natural teeth¹³⁶.

As for in-vitro testing of zirconia-based implant-supported restorations, a device which simulates the mastication loads present in the oral cavity was used in Att et al study¹³⁸. They evaluated the performance of implant-supported zirconia-based crowns in bi-layered structure on different abutments. The study revealed that zirconia-based crowns used in the anterior region could survive thermal cycling as well as 1,200,000 dynamic loading cycles with no failures. In addition, implant-supported bi-layered zirconia-based restorations had a lower fracture resistance compared to metal-ceramic restorations after cyclic loading¹³⁹. Moreover, zirconia frameworks veneered with feldspathic porcelain had lower fracture resistance compared to restorations veneered with glass ceramics¹³⁹. In the same context, Albrecht et al reported that veneering material also had an influence on the fracture strength of zirconia-based restorations¹⁴⁰.

Fracture of the veneer in the bi-layer structure remains the major clinical reason for technical complications in the posterior region¹⁴¹. Hence, manufacturing zirconia-based monolithic crowns would offer solution to the high chipping rate reported in the bi-layer zirconia-based restorations^{142,143}.

In-vitro study conducted by Beuer et al revealed that monolithic zirconia crowns had higher fracture resistance to static loading compared to veneered zirconia crowns¹⁴⁴. In a recent study on implant-supported zirconia-based restorations; crowns with monolithic structure had significantly higher fracture resistance compared to bi-layered structure¹⁴⁵.

Whether veneer chipping is associated with one system more than the other is still unknown. However, fracture (chipping) of zirconia-based crowns is influenced by the veneering material thickness as well as its mechanical properties. Also, any internal defects/damage¹⁴⁶ or residual stresses¹⁴⁷ present in the veneering material, framework design¹⁴⁸, firing/cooling protocol⁸⁷ and veneering methods^{140,149} may lead to veneer chipping in zirconia-based restorations.

Although monolithic structures reduce the potential of veneer chipping by removing the core-veneer interface, they are often opaque and offer less esthetics compared to bi-layer veneered structures. Thus, bi-layered implant-supported crowns are still a common practice.

1.4 Implant-supported hybrid-abutment zirconia-based crowns approach

A new approach for implant-supported restorations is the hybrid-abutment approach^{150,151}. It is believed that this approach is able to provide a combination of strength and aesthetics together^{150,151}. When using the hybrid-abutments to restore implant-supported crown, the hybrid-abutment crown is then consist of three components: a) an all-ceramic crown, b) an all-ceramic abutment and, c) a Ti-Base abutment. It was first used in implant supported prosthesis^{152,153}, and Drago et al proposed that frameworks used in the implant-supported prosthesis must be made of rigid materials, and designed to provide the needed support during mastication¹⁵².

Clinical studies on hybrid-abutment crowns; by Lin et al¹⁵⁰ (2014) and Hornbrook¹⁵¹ (2015) proposed that the use of hybrid-abutments made of pressed lithium disilicate is an adequate approach to enhance aesthetic in the anterior region for single crowns. However, Lin et al considered that using the pressing technique in the fabrication of the customised lithium disilicate abutments as a limitation due to the time and cost it needs¹⁵⁰.

Only few in-vitro studies have looked at the use of hybrid-abutments¹⁵⁴⁻¹⁵⁶ and their influence on the fracture resistance of all-ceramic crown^{154,155}. According to Honda et al, monolithic zirconia crowns cemented to Ti-Base had the highest fracture resistance value compared to the bi-layer zirconia-based restorations¹⁵⁵. Kelly (2016) on the other hand concluded that the abutment's material, manufacturer and design¹⁵⁶, all have an influence on the fracture resistance of all-ceramic crowns. Also, monolithic lithium disilicate crowns supported by hybrid-abutments showed comparable fracture resistance results to all-metal abutment systems under fatigue¹⁵⁴. However, Silva et al stated that success of the hybrid-abutment crown system is limited by degradation to the abutment screw caused by the fatigue¹⁵⁴.

Prior to applying materials for clinical use, in-vitro tests have to be undertaken to prove materials' performance and applicability. Such tests can be performed in a short period of time with a standardised test parameters¹⁵⁷, and its results are more clinically relevant when the tests conducted closely simulate the clinical conditions¹¹. A device that artificially simulates the oral environment has been developed to evaluate the dental restorative systems under more clinically relevant conditions^{11,157}. The device introduces a comparable cyclic fatigue component and simulates the physiological oral environment by exposing the test specimens to dynamic loading, moisture, and thermal changes.

1.5 Aim of the study

Currently, literature has very limited data on the fracture resistance of hybrid-abutment crowns. Therefore, the aim of this study was to investigate fracture resistance and post fatigue fracture load of implant-supported hybrid-abutment all-ceramic crowns. Crowns were fabricated in different structures (monolithic and bi-layer) using different all-ceramic materials and different fabrication techniques.

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Linking page

Chapter one presented a review of the relevant literature on zirconia-based restorations which will be the focus of this research. Zirconia has recently being used in prosthodontics both as a crown material as well as an abutment material. Description of all-ceramic materials, influence of the different crown structures recently being manufactured, as well as the influence of testing/clinical environment on the all-ceramic crown strength were also discussed.

The next chapter is published in a peer-reviewed journal (Journal of Clinical and Investigative Dentistry). It is a systematic review article which aimed to study the influence of different aqueous in-vitro testing methodologies on the survival results of zirconia-based restorations, and assess the level of agreement between in-vitro and previous in-vivo data.

Bibliography of the paper is as follows:

Elshiyab S.H, Nawafleh N, George R. Survival and Testing Parameters of Zirconia-Based Crowns Under Cyclic Loading In An Aqueous Environment: A Systematic Review. *J Invest Clin Dent.* 2017;8.

Chapter Two

**Survival and testing parameters of zirconia-based
crowns under cyclic loading in an aqueous
environment: A systematic review**

(Published paper)

STATEMENT OF CONTRIBUTION TO CO-AUTHORED PUBLISHED PAPER

This chapter includes a co-authored paper. The bibliographic details (if published or accepted for publication)/status (if prepared or submitted for publication) of the co-authored paper, including all authors, are:

Elshiyab S.H, Nawafleh N, George R. Survival and Testing Parameters of Zirconia-Based Crowns Under Cyclic Loading In An Aqueous Environment: A Systematic Review. The paper is published in Journal of Clinical and Investigative Dentistry (J Invest Clin Dent. 2017;8).

My contribution to the paper involved: study protocol, databases search, studies selection and arrangement and preparation of the manuscript.

(Signed)

May 2017

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May 2017

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May 2017

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2.1 Abstract

Aims: To study the hypothesis that in-vitro fatigue testing variables in aqueous environment affect the survival results of zirconia-based restorations, and evaluate the level of agreement between in-vitro and previous in-vivo data.

Methods: An electronic search of literature was conducted in PubMed and Scopus to identify in-vitro studies testing zirconia-based crowns using cyclic loading in aqueous environment. Only studies that complied with the inclusion criteria were included. Data extracted was used for survival analysis and assessment of in-vitro parameters for fatigue testing of implant and tooth-supported crowns. Using [AMSTAR], recent in-vivo systematic review studies were assessed prior to consideration for comparison with the current in-vitro data.

Results: After applying the inclusion criteria only 25 articles were included. Five-year cumulative survival rate of zirconia-based implant-supported crowns was lower than tooth-supported crowns (84% and 88.8% respectively). Tooth-supported crowns subjected to wet fatigue showed a lower 5-year cumulative survival rate compared to thermal cycling (62.8% and 92.6% respectively). Monolithic crowns showed higher fracture resistance compared to bi-layer structure (pressed or hand-layered). Only in-vivo systematic reviews, which complied with AMSTAR assessment criteria, were used for comparison to the in-vitro data. As for fatigue testing parameters; differences in the experimental setting were evident and affected the outcomes.

Conclusions: Crown survivals depend on type of support, type of fatigue test conducted, crown structure, and veneering method. In-vitro fatigue testing protocols are highly variable which introduce a need for international standardisation to allow for more valid comparability of data.

2.2 Introduction

All-ceramic crown systems are popular because they are mechanically strong, biocompatible and can meet the aesthetic demands of patients¹⁻⁴. A number of all-ceramic systems are currently available; with glass ceramic (e.g. lithium disilicate and leucite), and oxide ceramics (e.g. alumina and zirconia) appearing to be the most popular⁵. Despite the significant strength and aesthetic advantages of these materials, the relatively high failure rates, especially in the posterior region represent their major drawback^{6,7}.

Veneer fracture (chipping) usually originates in contact loads resulting in wear facets⁸, which might later generate a crack and propagate to the surface leading to fracture. It is considered one of the major downside of zirconia-based restorations^{9,10}. Previous studies have showed that the survival of all-ceramic restorations is limited by the greater incidence of veneer chipping and/or core fracture when compared to that of metal-ceramics¹¹⁻¹⁹. It has also been reported that the survival rate of all-ceramic restorations is generally influenced by the core design and the support it provides to the veneering ceramic, as well as the thickness of the ceramic material^{20,21}.

Crowns made of materials such as lithium disilicate, leucite, and aluminium oxide have shown good clinical long-term outcomes and therefore are considered as the standard of care for crowns in anterior teeth replacements^{22,23}. Nevertheless, their tendency to fractures could be a major clinical reason that limits their use in restoring posterior teeth²⁴. In terms of strength; zirconia represents the strongest dental ceramic material available; with the ability to withstand high occlusal loads²⁵⁻²⁷.

Zirconia-based restorations can be either monolithic or bi-layer. Compared to monolithic structures, stress distributions and load bearing ability vary in the layered structure (veneer); therefore differences in mechanical behaviour as well as fracture

frequency could be expected²⁸. However, when used as a framework, zirconia-based restorations have an estimated survival rate greater than 20 years^{29,30}. A major drawback of zirconia is that it has reported a greater incidence of veneer chipping compared to metal-ceramic and other all-ceramic materials^{9,11,31,32}.

Undeniably, clinical trials can more precisely reflect the actual performance of a dental material. However, clinical trials are time-consuming and difficult to standardise³³. In addition, in-vivo survival data vary and are often difficult to compare, due to the difference in study parameter and ceramic material tested⁵. On the other hand, in-vitro experiments provide basic information about the restorations mechanical properties and help assessing the failure risk by closely imitating clinical conditions³⁴.

To authors' knowledge, there is currently no systematic review on the in-vitro survival of zirconia based restorations, the level of agreement between in-vitro and in-vivo outcomes, and the degree to which simulated laboratory data represent clinical outcomes. Therefore, the aim of this systematic review was to explicate the in-vitro short- and long-term survival rate of tooth-supported and implant-supported zirconia-based crowns. The systematic in-vitro review data will then be compared against previous in-vivo clinical data to evaluate the level of agreement.

2.3 Materials and Methods

The primary questions addressed in the current review were:

- **What is the in-vitro survival rate of zirconia-based crowns in both; tooth-supported and implant-supported in aqueous environment, and what is the level of agreement with in-vivo survival data?**
- **What were the in-vitro testing parameters used in assessing survival and strength of zirconia-based crowns and are they clinically relevant?**

2.3.1 Search strategy and study selection

An electronic search of the literature was conducted in PubMed and Scopus, to identify in-vitro studies tested zirconia-based crowns using fatigue loading in aqueous environment. Publication date was set up to Jan 31st, 2015 and language was set to English. The search was conducted using Boolean operators and the combinations of the following keywords and phrases; zirconia, YTZP, Y-TZP, all-ceramic, fatigue, survival, aging, cyclic load*, dynamic load*, laboratory simulation, life time, thermal cycling, fracture, strength, fracture resistance, implant-supported, tooth-supported, crown, superstructure*, crowns, and in-vitro.

The electronic search was followed by manual search in the major journals in prosthodontics; Journal of Prosthodontics, International Journal of Prosthodontics, Dental Materials, Quintessence International and Journal of Oral Rehabilitation. Moreover, references of the included articles were revised for potential inclusions. Grey literature was avoided as it was difficult to access all electronically available literature

Search results were then transferred to EndNote[®] referencing software (Thomson Reuters, PA, USA) where duplicates were removed. Then, titles of all the articles were screened and irrelevant articles were excluded. Later, abstracts of the proposed included articles were reviewed according to the following inclusion criteria:

- Article published in a peer-reviewed journals
- In-vitro studies used anatomically correct crowns samples
- Experimental design involved cyclic loading in aqueous conditions
- Studies clearly stated either framework or veneering material was zirconia-based
- Magnitude of force and number of cycles applied should be mentioned

Databases search, initial title and abstract screening were conducted independently by two reviewers. Only studies that complied with the inclusion criteria were assessed further. Abstracts which did not provide sufficient information were forwarded to full-text review. Finally, full-text articles were reviewed considering the earlier mentioned inclusion criteria. When data was duplicated in more than one publication, only the earlier published article was included. During the full-text review, if both reviewers did not agree on the inclusion/ exclusion of a certain paper, it was then forwarded to a third reviewer to elect. Search strategy and study selection are illustrated in figure 2.1.

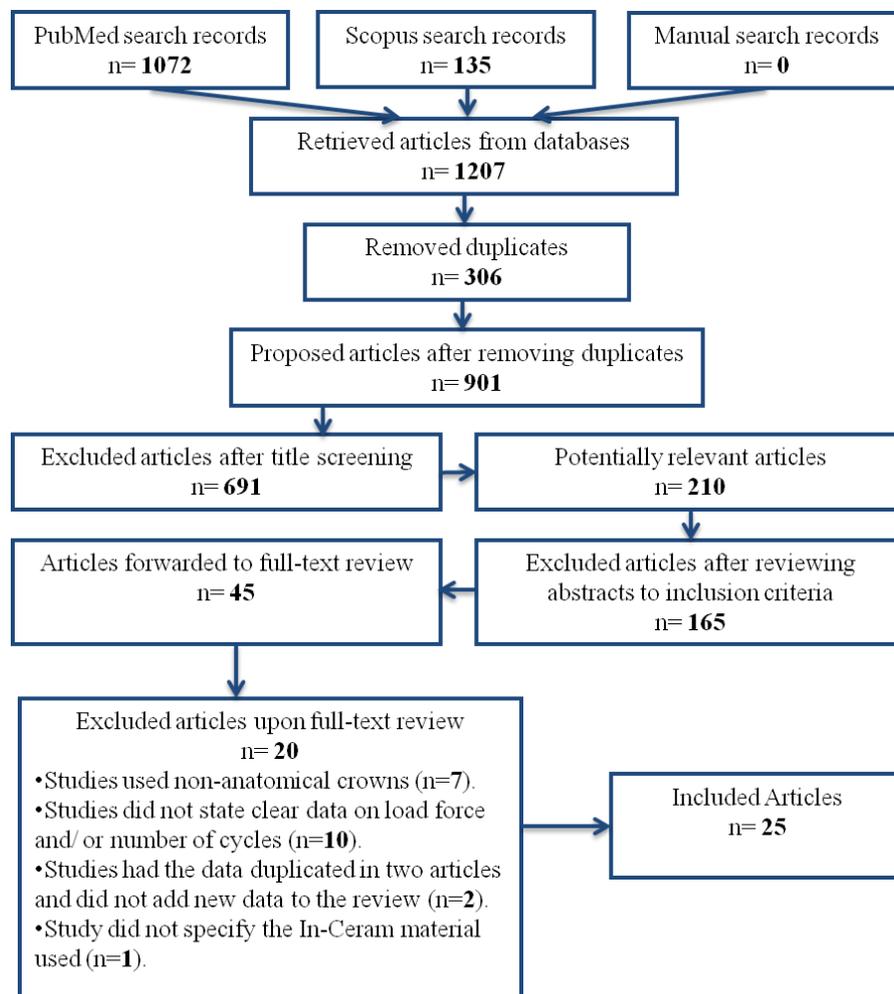


Figure 2.1. Flow chart describing the search strategy and study selection procedure

For the purpose of this systematic review, survival was defined as the crowns remaining clinically acceptable with no visible chipping in the veneer and/or core. Failures were any veneer chipping or crown bulk fracture which needs a remake or repair.

2.3.2 Data extraction and survival analysis

Data extraction of all included studies was conducted in two stages and entered in two different Excel[®]MS[®] sheets. Stage one included data needed to run the survival analysis of the two groups (tooth-supported and implant-supported). Data extracted was; author name, date of the study, sample size, maximum numbers of cycles applied, number of cycles at failure (time interval), total number of crowns in interval and number of crowns failed in interval. Time intervals were set to 2 years period starting at baseline time of 0. A number of 250,000 cycles was used to represent a simulation of one clinical year^{35,36}. Interval's probability of failure (Pf), probability of survival (Ps) and cumulative rates (Cs) were calculated according to the following equations:

$$\text{Failure rate}_{(\text{interval})} = \# \text{ failed crowns}_{(\text{interval})} / \# \text{ crowns}_{(\text{interval})}$$

$$\text{Survival rate}_{(\text{interval})} = \# \text{ crowns}_{(\text{interval})} - \# \text{ failed crowns}_{(\text{interval})} / \# \text{ crowns}_{(\text{interval})}$$

$$\text{Cumulative survival}_{(\text{interval})} = \text{Ps}_{(\text{current})} \times \text{Cs}_{(\text{previous})}$$

For survival rate calculations, the number of cycles at which the crowns failed was considered. When the number of cycles at which failures had occurred was not reported, samples were considered to have failed at the maximum number of cycles used in that study. Also, studies that did not report any crown failure were considered to have had a 100% survival at the maximum number of cycles used in that particular study. To evaluate the level of agreement of this in-vitro survival rate data to clinical studies, recently published in-vivo systematic review papers on survival of zirconia restorations were assessed using the quality-ranking checklist for Assessing the Methodological

Quality of systematic Reviews (AMSTAR)^{37,38}, prior consideration to using as baseline for comparison.

Stage two included data needed for assessing the in-vitro parameters used in fatigue testing for both implant-supported and tooth-supported crowns. Whether samples underwent wet fatigue at constant temperature or with thermal cycling (TC) was also identified at this stage. Data extracted was; author name, year of publication, sample size, crowns location, crowns type, periodontal ligament simulation, framework and veneering materials, fabrication technique and manufacturing companies, fatigue testing machine, TC temperature and settings, number of cycles, force magnitude and frequency, abutment material and shape, material, size and shape of the antagonist (indenter) as well as studies results.

2.4 Results

Using the combination of the previously mentioned keywords, the search yielded 1207 articles. After removing duplicates (306), 901 titles were screened for possible inclusion resulting in the rejection of 691 papers. The remaining 210 articles went forwarded to the abstract stage; of them, 45 articles were qualified for full-text review. After cross-matching the full-text articles to the inclusion criteria, only 25 articles were included. The manual search through the reference list of the included papers did not provide any additional studies.

Twenty studies were excluded at the full-text reading stage for the following reasons:

- Seven studies did not have anatomical crown geometry^{27,30,39-43}.
- Ten studies did not state a clear data on magnitude of force and/ or number of cycles⁴⁴⁻⁵³.
- Two studies had the data duplicated in two publications^{54,55}.
- One study did not specify the In-Ceram material (zirconia or alumina) used⁵⁶.

The recent in-vivo systematic reviews^{19,57} that adhered with AMSTAR quality ranking checklist were used as baseline to compare the current result. For the purpose of clarity this will be discussed in the discussion.

Dental crowns were tested in two structural forms; monolithic or bi-layer (Table 2.1). While monolithic crowns were fabricated using Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) milling systems, bi-layer crowns were hand-layered, pressed or bonded to the milled zirconia framework. The incident of veneer fracture (chipping) was reported in the bi-layer crowns while monolithic crowns reported no incidence of chipping. Veneers of hand-layered crowns had a higher fracture incidence compared to pressed or milled veneers.

Table 2.1 Crowns type, zirconia brand used and veneering technique of the included studies

Author (Year)	Crowns type	Crown structure	Core material/ Brand	Veneering material brand/ Technique
Paula et al ⁵⁸ (2015)	Tooth-supported	Bi-layer	Pre-sintered Y-TZP blocks/IPS e.max ZirCAD, Ivoclar Vivadent, Schaan, Liechtenstein	IPS e.max Ceram, Ivoclar Vivadent, Schaan, Liechtenstein/Hand-layered
Baladhan day-utham et al ⁵⁹ (2015)	Tooth-supported	Bi-layer and Monolithic	Zirconia (LAVA; 3M ESPE) for both frameworks and monolithic crowns	1. LAVA Ceram, 3M ESPE/Hand-layered 2. IPS e.max Ceram, Ivoclar Vivadent, Schaan, Liechtenstein /Hand-layered 3. LAVA DVS, 3M ESPE/Milled
Amir Rad et al ⁶⁰ (2015)	Tooth-supported	Bi-layer	Pre-sintered Y-TZP blocks/IPS e.max ZirCAD, Ivoclar Vivadent, Schaan, Liechtenstein	IPS e.max ZirPress, Ivoclar Vivadent, Schaan, Liechtenstein/Pressed
Preis et al ³ (2014)	Tooth-supported	Bi-layer	Y-TZP/Cercon base, DeguDent	Cercon Ceram Kiss, DeguDent/Hand-layered
Nicolaisen et al ⁶¹ (2014)	Tooth-supported	Bi-layer	Y-TZP/BeCe CAD Zirkon, Bego, Bremen, Germany	VITA VM 13 and VITA VM 9, VITA Zahnfabrik, Germany/Hand-layered
Johansson et al ⁶² (2014)	Tooth-supported	Bi-layer and monolithic	Zirconia/Metoxit AG, Thayngen, Switzerland and Sagemax Bioceramics, Inc.,	IPS e.max Ceram, Ivoclar Vivadent, Schaan, Liechtenstein /Hand-layered

			Federal Way, WA for both frameworks and monolithic crowns	
Altamimi et al ⁶³ (2014)	Tooth-supported	Bi-layer	Zirconia	IPS e.max ZirPress, Ivoclar Vivadent, Schaan, Liechtenstein/Pressed
Schmitter et al ⁶⁴ (2012)	Tooth-supported	Bi-layer	Zirconia/Sirona inCoris ZI, mono L F1, CEREC Bloc; Sirona, Bensheim, Germany	1. CEREC Bloc, Sirona/Milled 2. Conventional porcelain/Hand-layered
Preis et al ²¹ (2013)	Tooth-supported	Bi-layer	Y-TZP/Lava, 3M ESPE, Germany	1. Lava Ceram, 3M ESPE, Germany/Hand-layered 2. IPS e.max ZirPress, Ivoclar Vivadent, Schaan, Liechtenstein/Pressed 3. Experimental material, 3M ESPE, Germany/Digitally veneered
Alhasanyah et al ⁶⁵ (2013)	Tooth-supported	Bi-layer	Zirconia	Jensen Creation ZI, Jensen Dental Inc./Hand-layered
Abousheli b ⁶⁶ (2013)	Tooth-supported	Bi-layer	Zirconia/Cercon, Degudent, Hanau Wolfgang, Germany	Ceram Press, Degudent, Hanau Wolfgang, Germany/Pressed
Stawarczyk ⁶⁷ (2012)	Tooth-supported	Bi-layer	Y-TZP/ZENO ZR, Wieland Dental, Germany	1. Triceram, Wieland, Germany/Hand-layered 2. Zirox Wieland, Germany/Hand-layered 3. VITA VM9 Vita Zahnfabrik, Germany/Hand-layered
Hosseini et al ⁶⁸ (2012)	Implant-supported	Bi-layer	1. Y-TZP/Everest ZS (Kavo Everest); Kavo Germany 2. Procera AllZirkon/Procera AllZirkon; Nobel Biocare, Göteborg, Sweden	1. HeraCeram Zirkonia; Heraeus Kulzer/Hand-layered 2. IPS e.max Ceram; Ivoclar Vivadent, Schaan, Liechtenstein/Hand-layered
Beuer et al ⁶⁹ (2012)	Tooth-supported	Bi-layer and monolithic	1. Pre-sintered zirconia/ZirLuna, ACF, Amberg, Germany for both framework and monolithic crowns 2. Pre-sintered Y-TZP blocks/IPS e.max ZirCAD, Ivoclar Vivadent, Schaan, Liechtenstein	1. IPS e.max Ceram IV; Ivoclar Vivadent, Schaan, Liechtenstein/Hand-layered 2. IPS e.max CAD/Ivoclar Vivadent, Schaan, Liechtenstein/Milled
Abousheli b ⁷⁰ (2012)	Tooth-supported	Bi-layer	Zirconia/ Cercon, Degudent, Hanau Wolfgang, Germany	Cercon Press, Degudent, Hanau Wolfgang, Germany/Pressed

Stawarczyk et al ⁷¹ (2011)	Tooth-supported	Bi-layer	Y-TZP/ ZENO ZR, Wieland Dental	<ol style="list-style-type: none"> 1. PressX Zr, Wieland Dental, Germany/Pressed 2. Gc Initial IQ LF, GC Europe, Belgium/Pressed 3. Vita PM9, Vita Zahnfabrik, Germany/Pressed 4. IPS e.max ZirPress, Ivoclar Vivadent, Schaan, Liechtenstein/Pressed 5. Zirox, Wieland Dental, Germany/Hand-layered 6. GC Initial ZR, GC Europe, Belgium/Hand-layered 7. Vita VM9, Vita Zahnfabrik, Germany/Hand-layered 8. IPS e.max Ceram, Ivoclar Vivadent, Schaan, Liechtenstein/Hand-layered
Albrecht et al ⁷² (2011)	Implant-supported	Bi-layer	Straumann Anatomical IPS e.max Abutments/Straumann, Basel, Switzerland	<ol style="list-style-type: none"> 1. IPS e.max CAD, Ivoclar Vivadent, Schaan, Liechtenstein/Milled 2. IPS Empress CAD, Ivoclar Vivadent, Schaan, Liechtenstein/Pressed 3. IPS e.max Ceram, Ivoclar Vivadent, Schaan, Liechtenstein/Hand-layered 4. IPS e.max ZirPress, Ivoclar Vivadent, Schaan/ Pressed
Senyilmaz et al ⁷³ (2010)	Tooth-supported	Bi-layer	<ol style="list-style-type: none"> 1. Zirconia/Cercon, Degussa Dental, Hanau, Germany 2. Zirconia/Vita In-Ceram Zirconia, Vivadent, Germany 3. Zirconia/Procera AllZircon, Nobel Biocare, Sweden 	<ol style="list-style-type: none"> 1. Specially tailored low-fusing dental ceramic/Hand-layered 2. Vitadur Alpha porcelain, Vivadent, Germany/Hand-layered 3. Triceram/Hand-layered
Rues et al ⁷⁴ (2010)	Tooth-supported	Bi-layer	Zirconia/Cercon Base; DeguDent, Hanau, Germany	<ol style="list-style-type: none"> 1. Cercon Ceram Kiss (CCK)/Hand-layered 2. Cercon Ceram Love (CCL)/Hand-layered
Lorenzoni et al ⁷⁵ (2010)	Tooth-supported	Bi-layer	Y-TZP/IPS e.max ZirCAD, Ivoclar Vivadent, Schaan, Liechtenstein	IPS e.max Ceram, Ivoclar Vivadent, Schaan, Liechtenstein/Hand-layered
Attia ⁷⁶ (2010)	Tooth-supported	Bi-layer	In-Ceram zirconia/Vita, Bad Sackingen, Germany	VITA VM7, Vita, Bad Sackingen, Germany/Hand-layered
Rosentritt et al ⁷⁷ (2009)	Tooth-supported	Bi-layer	Y-TZP/ Cercon Base, Degudent, Hanau, Germany	Cercon Kiss. DeguDent, Hanau, Germany/Hand-layered

Rosentritt et al ⁷⁸ (2009)	Tooth-supported	Bi-layer	1. Ce.novation/ce.novation 2. Cercon/DeguDent 3. Digizon/Amann Girrbach 4. Lava/3M ESPE	1. ce.novation, Cercon Ceram Kiss/Hand-layered 2. Cercon Ceram Kiss, DeguDent/Hand-layered 3. Digizon, GC Initial, Amann Girrbach, GC Europe/Hand-layered 4. Lava Ceram, 3M ESPE/Hand-layered
Zahran et al ⁷⁹ (2008)	Tooth-supported	Bi-layer	YZ cubes/In-Ceram YZ, Vita Zahnfabrik	VM9, Vita Zahnfabrik, Germany/Hand-layered
Att et al ⁸⁰ (2006)	Implant-supported	Bi-layer	ZrO ₂ /Nobel Biocare, Stockholm, Sweden	Vita VM9; Vita Zahnfabrik, Bad Sackingen, Germany/Hand-layered

Tables 2.2-2.5 show the survival rates calculated using data extracted from the included studies. Table 2.2 presents life analysis of both tooth-supported and implant-supported studies. Tables 2.3 and 2.4 separate the analysis according to the aging technique into studies applied wet fatigue and others applied TC, in both tooth-supported and implant-supported studies respectively. Survival rate according to location in the oral cavity (anterior vs. posterior) in the tooth-supported studies is presented in table 2.5. Survival tables summarize both failure and survival rates according to time intervals; where 1 clinical year corresponds to 250,000 cycles during in-vitro testing^{35,36}.

The survival rates of tooth-supported zirconia-based crowns differed according to the aging technique; wet fatigue vs. thermal cycling mechanical loading (TCML). Nine studies reported on wet fatigue, and rendered an estimated 5-year cumulative survival rate of 62.8%, while 13 studies reported on TCML and rendered an estimated 92.6% 5-year cumulative survival rate. Cumulative survival rates calculated for zirconia-based crowns tested in wet environment were generally lower compared to those underwent TCML (Table 2.3). Moreover, implant supported crowns exhibited relatively lower 5-year cumulative survival rates compared to tooth-supported crowns (Table 2.2).

Table 2.2 Life table analysis for tooth-supported vs. implant-supported zirconia-based crowns

Crown Support	Time interval (clinical years)	No. of studies reporting interval	No. of crowns in interval	No. of crowns failed in interval	Interval failure rate (%)	Interval survival rate (%)	Cumulative survival rate (%)
Tooth	0-2	22	1155	28	2.4	97.6	97.6
	2-4	14	851	35	4.1	95.9	93.6
	4-6	12	822	42	5.1	94.9	88.8
	6-8	1	38	0	0	100	88.8
	8-10	1	38	0	0	100	88.8
	10-12	1	38	9	23.7	76.3	67.8
	12-14	1	38	9	23.7	76.3	51.7
Implant	0-2	3	84	13	16	84	84%
	2-4	3	71	0	0	100	84%
	4-6	3	71	0	0	100	84%
	6-8	3	71	0	0	100	84%

Table 2.3 Life table analysis for tooth-supported zirconia-based crowns underwent wet fatigue vs. TCML

Fatigue conducted	Time interval (clinical years)	No. of studies reporting interval	No. of crowns in interval	No. of crowns failed in interval	Interval failure rate (%)	Interval survival rate (%)	Cumulative survival rate (%)
Wet fatigue	0-2	9	254	6	2.4	97.6	97.6
	2-4	5	110	28	25.5	74.5	72.7
	4-6	3	88	12	13.6	86.4	62.8
	6-8	1	38	0	0	100	62.8
	8-10	1	38	0	0	100	62.8
	10-12	1	38	9	23.7	76.3	47.9
	12-14	1	38	9	23.7	76.3	36.5
TCML	0-2	13	901	22	2.4	97.6	97.6
	2-4	9	741	7	1	99	96.6
	4-6	9	734	30	4.1	95.9	92.6

Table 2.4 Life table analysis for implant-supported zirconia-based crowns underwent wet fatigue vs. TCML

Fatigue conducted	Time interval (clinical years)	No. of studies reporting interval	No. of crowns in interval	No. of crowns failed in interval	Interval failure rate (%)	Interval survival rate (%)	Cumulative survival rate (%)
Wet fatigue	0-2	1*	16	13	81.2	18.8	18.8
	2-4	1*	3	0	0	100	18.8
	4-6	1*	3	0	0	100	18.8
TCML	0-2	2**	68	0	0	100	100
	2-4	2**	68	0	0	100	100
	4-6	2**	68	0	0	100	100

* Hosseini M, Kleven E, Gotfredsen K (2012)

** Albrecht T, Kirsten A, Kappert HF, et al (2011)

** Att W, Kurun S, Gerds T, et al (2006)

Data extracted showed different experimental conditions and study designs, various ceramic manufacturing companies and several crown types. Materials tested were mostly manufactured by; Ivoclar Vivadent (Schaan, Liechtenstein), Vita Zahnfabrik (Bad Sackingen, Germany), Cercon DeguDent (Hanau Wolfgang, Germany) and LAVA 3M ESPE (Germany) (Table 2.1). Table 2.6 details the variables used in the in-vitro experiments of the included studies; antagonists (indenters) across studies varied in diameter (2.5mm-8mm), geometry (crown, ball, sphere or flat surface) and material (stainless steel, tungsten carbide, ceramic, metal-ceramic crown, composite or natural tooth). Fatigue testing apparatus varied among the included studies; chewing simulator was utilised in 11 studies^{3,21,64,69,72-74,76-78,80}, 13 studies utilised other fatigue machines^{58-63,65-68,70,75,79}, and one study did not report the fatigue machine used⁷¹. Ambient settings (aging) adopted were either wet environment at constant temperature or with TC; 15 out of 25 studies reported TC at 5°C-50/55°C^{3,21,60,62,67,69-73,77,78,80} or 6.5°C-60°C^{64,74} while the remaining 10 studies reported wet fatigue^{58,59,61,63,65,66,68,75,76,79}.

Table 2.5 Anterior vs. Posterior crowns: In-vitro life table analysis for tooth-supported zirconia-based crowns

Restoration location	Time interval (clinical years)	No. of studies reporting interval	No. of crowns in interval	No. of crowns failed in interval	Interval failure rate (%)	Interval survival rate (%)	Cumulative survival rate (%)
Anterior	0-2	6	611	15	2.5	97.5	97.5
	2-4	4	556	7	1.3	98.7	96.2
	4-6	4	551	3	0.6	99.4	95.6
	6-8	1	38	0	0	100	95.6
	8-10	1	38	0	0	100	95.6
	10-12	1	38	9	23.7	76.3	72.9
	12-14	1	38	9	23.7	76.3	55.6
Posterior	0-2	16	544	13	2.4	97.6	97.6
	2-4	9	284	28	9.9	90.1	87.9
	4-6	7	262	39	14.9	85.1	74.8

Table 2.6 In-vitro experimental variables used in included studies

Variable		Number of studies		
		Tooth-supported	Implant-supported	
Tooth restored	Anteriors	6 ^{60,66,67,70,71,74}	2 ^{68,80}	
	Premolars	1 ⁷⁶	1 ⁷²	
	Molars	15 ^{3,21,58,59,61-65,69,73,75,77-79}	N/A	
Abutment material	Ivory tooth	1 ⁶¹	N/A	
	Resin-based composite	6 ^{58,59,65,66,70,75}	N/A	
	PMMA	4 ^{3,21,62,77}	N/A	
	Metal dies	7 ^{60,63,64,67,69,71,74}	N/A	
	Epoxy resin	1 ⁷⁹	N/A	
	Natural tooth	3 ^{73,76,78}	N/A	
	Indenter/ antagonist	Geometry	Crown	3 ^{3,21,77}
Ball			7 ^{59,60,62,63,73,76,79}	2 ^{68,80}
Hemisphere			NA	1 ⁷²
Sphere			7 ^{58,61,64-66,74,75}	N/A
Flat			2 ^{67,71}	N/A
Size (diameter)		2.5mm	1 ⁶²	N/A
		3.0 mm	1 ⁷⁹	N/A
		4.0 mm	1 ⁷⁶	N/A
		5.0 mm	1 ⁶³	N/A
		6.0 mm	7 ^{59,61,64,65,73,74}	2 ^{68,80}
		6.36 mm	2 ^{58,75}	N/A
		8.00	1 ⁶⁰	N/A
		Material	Stainless steel	10 ^{58,60,62-64,66,69,74,75,79}
Tungsten carbide			2 ^{61,65}	N/A
Ceramic			3 ^{59,73,76}	1 ⁸⁰
Metal-ceramic crown			3 ^{3,21,77}	N/A
Composite			2 ^{67,71}	N/A
Natural-tooth	1 ⁷⁸		N/A	
Testing apparatus	Chewing simulator		9 ^{3,21,64,69,73,74,76-78}	2 ^{72,80}
	Other apparatus	12 ^{58-63,65-67,70,75,79}	1 ⁶⁸	
Ambient condition	Wet fatigue	9 ^{58,59,61,63,65,66,75,76,79}	1 ⁶⁸	
	TC 5°-50°/55°	11 ^{3,21,60,62,67,69-71,73,77,78}	2 ^{72,80}	
	TC 6.5°-60°	2 ^{64,74}	N/A	
Simulation of periodontal ligaments		7 ^{3,21,70,73,76-78}	N/A	

2.5 Discussion

2.5.1 Survival rate analysis

Overall, the survival analysis showed that cumulative in-vitro 5-year survival rate of tooth-supported crowns is 88.8%, which is relevantly close to the clinical rate reported in a previous systematic review⁵⁷ at 91.2% (Table 2.7). Crowns underwent TCML exhibited a cumulative 5-year survival rate of 92.6%, which looked to be more representative of clinical results (91.2%)⁵⁷. Surprisingly, crowns that underwent wet fatigue without TC (Table 2.3) exhibited lower cumulative 5-year survival rates (62.8%). It may be hence construed that TC is perhaps more appropriate over wet fatigue testing in simulating conditions exist in the oral cavity. Nevertheless, a study by Rosentrit et al showed that fracture resistance of all-ceramic fixed partial dentures was significantly reduced when using TCML compared to a constant temperature of 25°C⁸¹. It is therefore important to further investigate and compare fracture of zirconia crowns under both wet and TCML conditions to highlight reasons behind any differences if resulted. Similarly it was found that the in-vitro survival data for implant-supported crowns which underwent wet fatigue (18.8%)⁶⁸ was less representative to the clinical cumulative 5-year survival result reported in a recently published paper (97.1%)¹⁹. Differences between in-vitro to in-vivo survival rate of implant-supported crowns may possibly be due to a) imprecise simulation of the functional loads present in-vivo, b) crowns location and c) the small number of crowns included in the in-vitro simulations.

Table 2.7 In-vivo and in-vitro cumulative survival rates for zirconia-based crowns

Crowns Type	In-vitro/ In-vivo time period	In-vivo cumulative survival rate (%)	In-vitro cumulative survival rate (%)	
			Wet fatigue	TCML
Tooth-supported	1-year	100 ¹⁹	97.6	97.6
	3-years	95 ¹⁹	72.7	96.6
	5-years	91.2 ⁵⁷	62.8	92.6
Implant-supported	1-year	100 ¹⁹	18.8	100
	3-years	96 ¹⁹	18.8	100
	5-years	97.1 ¹⁹	18.8	100

The current in-vitro survival analysis showed difference in survival rate between tooth- and implant-supported crowns. Implant-supported crowns had higher veneer fracture rates thus its 5-year cumulative survival rate was lower compared to tooth-supported crowns (84%, 88.8% respectively), which agrees with previous in-vivo studies^{82,83}. Such difference can be linked to the differences in the components of the implant-supported crowns with the dental implant and the abutments^{84,85}. Furthermore, veneering ceramic in implant-supported crowns is subjected to loads higher than its strength due to the support of the rigid abutment, which leads to higher fracture rates than tooth-supported crowns according to in-vitro studies^{84,85}. It is worth mentioning that veneering material becomes the weak link in both tooth and/or implant-supported crowns, since it is subjected to loads that exceed its strength, resulting in fractures of the veneering material in the in-vivo setting⁸⁴.

Structure of zirconia-based crowns can be either monolithic or bi-layer. According to the reviewed studies; monolithic crown structure has proven to be more resistance to fatigue than the bi-layer structure. The higher fracture resistance of monolithic crowns

compared to the veneered crowns can be attributed to the monolithic application of the high quality zirconia blanks used in the CAD/CAM milling of the full contour crowns^{86,87}; this eliminates the core-veneer bond problem and produces high strength structure. In contrast, in the bi-layer zirconia-based structures; core-veneer bond is weaker than any other all-ceramic system⁸⁸, and therefore can prompt delamination and chipping in the veneering ceramic. Another weakening factors in the bi-layer systems are the presence of “impurities” within the veneer layer³⁹, laboratory differences in handling conditions during fabrication, sintering⁸⁹, grinding of zirconia structures and air abrasion which creates cracks and various level of damage^{90,91}. All these factors can affect stress distribution as well as load bearing ability of the restorations in service⁹².

Bi-layer crowns in the included studies were either hand-layered (18/22 studies), pressed (6/22 studies) or milled (3/22 studies). The only technique that showed consistent 100% survival rate was the milling technique. Schmitter et al reported higher strength and 100% survival of milled veneering technique compared to hand-layered veneering (87.5%)⁶⁴. On the other hand, pressing and hand-layering techniques showed failure at different rates, where hand-layered crowns had the lowest survival rates. Survival results were inconsistent among the included studies reporting on each technique, ranging from 100%^{60,62,73} and reaching 0% at an estimated 4 years clinical function⁶¹ in the hand-layered structures. Schmitter and colleagues⁶⁴ studied chipping of zirconia-based molar crowns veneered using CAD/CAM compared to hand-layering technique. They reported significant failure differences between the two groups; while no failures occurred in any of the CAD/CAM veneered crown, failures occurred in almost all the hand-layered veneered ones (7/8). They reported 87.5% failure rate as early as about 120,000 cycles which represents less than one clinical year. This has led to the conclusion that CAD/CAM veneered crown were less susceptible to aging than crowns with hand-layered structures.

It is noticeable that none of the included studies reported on loss of retention and/or screw loosening, although these complications were commonly reported in-vivo as frequent technical complications occurring beside fracture of the veneering material^{19,57,82}. The standardised study design in laboratory simulations might be responsible for the absence of these complications in-vitro. Clinically, the performance of a restoration is influenced by a combination of factors such as patient factors (age, tooth history, frequency of treatment, gender and age), dentist factors and tooth position; all these factors can influence the reported survival rates^{93,94}.

2.5.2 Fatigue testing parameters

Clinical trials can provide the best and final evaluation for materials used in restorative dentistry⁸¹. However, they might be limited by time constraints, costs, the need for adequate number of restorations and long observation time⁹⁵. In addition, ethical approvals are often difficult to obtain^{95,96}. Hence, in-vitro studies are essential to evaluate new materials and predict its lifetime and failures prior to in-vivo placements⁹⁷.

Numerous in-vitro testing approaches have been used to assess dental materials, with “Crunch the crown test”, which involves loading the crown with a ball indenter till failure, being the simplest⁹². Outcomes of these tests are of high fracture strength as well as high strength values. Also, failure modes occurring in these tests differ from those reported clinically³⁴. Recently, fatigue testing has become a more popular in-vitro approach for studying ceramic materials behaviour and assess their failure. In fatigue, the material is subjected to continuous and repetitive cyclic loading which leads to a localized yet progressive structural damage⁹⁸.

Despite the fact that all reviewed studies conducted fatigue testing, the experimental conditions applied to determine the fracture strength and failure reported were variable. Different fatigue machines, loading magnitudes and frequencies and number of cycles

were applied. In addition, there were various simulations of the ambient conditions in the oral cavity; temperature (TC setting), antagonist and abutments as well as periodontal ligament simulation. All these variables might impact the mechanical behaviour of zirconia-based crowns and influence the results.

Mastication devices have the ability to simulate clinical mastication loading (ML), including the force amount and frequency. Others simulate temperature fluctuation by means of TC. Force applied can be either weight, via electric motor or compressed air. However, a study by Rosentritt et al showed that applying the force with either pneumatic or weight using different mastication devices resulted in no significance on the loading capacity of the tested samples⁸¹. Fatigue machines used in the included studies varied with chewing simulator^{3,21,54,55,69,72-74,76,77} and custom-made cyclic loading or pneumatic machine^{60,66,67,70} being the ones most frequently used.

Force magnitude, frequency and direction are important factors which can contribute to failure of the veneering ceramic, and should be considered in testing⁶. It is noticeable that the magnitude of force used in the included studies varied considerably. While some studies used a constant low force magnitude^{3,21,54,59,67,69,71,73,76-78} others applied relatively high loads aiming to simulate a worst-case scenario^{61,68,79}. The high loads applied in these studies might explain the higher incidence of chipping resulted during cyclic loading⁹⁹. This is evident in a study by Nicolaisen and colleagues⁶¹ who reported 0% survival rate of hand-layered zirconia frameworks, where the load used was unrealistically high compared to loads occurring during normal masticatory function.

There was also a variation in the frequencies used in the included studies (when mentioned). The majority of the studies used low frequencies (1-2Hz)^{3,21,58,60,62,63,67,73,76}, but others used higher frequencies (10-20Hz)^{61,65,79}. A study by Rosentritt and colleagues has also showed that the mean in-vivo frequency was 1.2Hz⁸¹. Zhang and

colleagues, tested zirconia structures under cyclic loading at frequencies 0.1 and 10Hz, and their results showed significantly greater strength degradation of the tested structures at higher frequencies¹⁰⁰. However, in another study⁸¹ loading the all-ceramic structures between 1.6 and 3Hz had no significant influence on the structure's fracture force.

As for the lateral movement, it was mentioned in only two of the included studies^{69,76}. In literature, a human first molar was found to have an average lateral movement of 0.3 mm in non-bruxist human¹⁰¹. Nevertheless, when applied with fracture and aging testing, it showed no significant influence on the tested all-ceramic structures⁸¹. However, it may be essential when measuring wear of materials⁸¹.

Restorative materials used in dentistry, should have the capability to withstand the surrounding environment in the oral cavity, including temperature changes¹⁰². The chemical effect of the water in weakening zirconia has been well documented in the literature^{103,104}. Water has been reported to be one of the most effective agents to promote acceleration of the tetragonal to monoclinic phase transformation^{105,106}. Unlike all other ceramic materials, zirconia may go through low thermal/temperature degradation (LTD) or so called "Aging" causing strength degradation^{106,107}. TC can help mimic temperature fluctuation in the oral environment. Such fluctuation is reported to induce residual stresses to the framework-ceramic interface¹⁰⁸ and weakens the adhesion strength between the two layers. Several studies measured the mean high and low temperatures patients can tolerate in the oral cavity; they concluded that temperatures range of 5-55°C and 6.5-60°C are both acceptable by patients in both cold and hot oral test settings¹⁰⁹. Studies included in this review were all done in an aqueous environment. However, as shown in table 2.8, different TC protocols (when reported) were applied.

Table 2.8 Thermal cycling settings adopted by the included studies

Thermal cycling temperature (°C)	Duration (sec)/ Cycle	Number of cycles
5°C-55°C	60 ^{60,62,73,80} , 105 ⁷² , 120 ^{3,21,77,78}	320 ⁶⁹ , 1000 ⁶⁰ , 3000 ⁷⁸ , 5000 ^{62,70} , 6000 ^{3,21,77} , 10.000 ⁷³
5°C-50°C	120 ^{67,71}	6000 ⁶⁷
6.5°C -60°C	Not mentioned	10.000 ^{64,74}

The antagonist and abutment used during chewing simulation are also important factors to consider. Detailed information about the abutment and antagonist used in the included studies is listed in table 2.6. Previously conducted in-vitro studies have found that using different abutment materials influences the aging process^{110,111}. Abutments' modulus of elasticity plays a significant role on fracture resistance of all-ceramic crowns^{112,113}. the lower the abutment's modulus of elasticity, the higher the crowns frequency of fractures. When alloy abutments were used, fracture resistance of all-ceramic structure was overestimated⁸¹ compared to the crowns attached to human or polymeric abutments. In regard to the antagonists, as shown in table 2.6, antagonist used in the reviewed studies varied in material, shape and size. Ideally, enamel would be considered the material of choice for in-vitro simulation of restorative materials. However, natural teeth vary in morphology and require an extensive machining process for manufacturing which makes it less convenient and precise¹¹⁴. The use of human teeth as an antagonist decreased the fracture resistance of the all-ceramic structures compared to steatite ball antagonists⁸¹. Under long-term cyclic loading, in-vitro testing of anatomically correct crowns with a plate or sphere antagonist, might be a good approach to understand the clinical flaw mechanism, however hard to predict¹¹⁵.

In natural dentition, periodontal ligaments play an important role in stress distribution when a load is applied on a tooth¹¹⁶; hence, simulation of periodontal ligament is another important aspect to consider during in-vitro testing to closely mimic clinical situations¹¹⁷. However, only 7 included studies considered this factor^{3,21,70,73,76-78}.

Literature showed that different materials were used in the reproduction of periodontal ligaments; elastomeric impression materials being the most popular¹¹⁷⁻¹¹⁹. Soares and colleagues study¹²⁰ showed that stress distribution and fracture resistance varied considerably when periodontal ligaments were simulated; due to the high resilience of the acrylic resin and therefore can withstand and absorb higher forces. Moreover, fracture resistance significantly decreased by 70% when human teeth antagonist were associated with human abutments and the use of artificial periodontium⁸¹. Beside periodontal ligaments, simulation of tooth supporting structures by embedding their roots is another crucial factor to consider¹²¹. Different materials can be used for embedment in fracture tests¹²²⁻¹²⁴. Such reproduction of both periodontal ligaments and the alveolar bone was considered by Rees in a finite element study as mandatory to include in any fracture test¹²⁵. However, the effect of using different materials in the reproduction of periodontal ligaments and the root embedment material in fracture resistance tests is still in debate.

2.6 Conclusions

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

- ✓ Tooth-supported crowns have a relatively higher 5-year cumulative survival rates than implant-supported crowns.
- ✓ In-vitro simulations involved TC resulted in more clinically representative 5-year cumulative survival rate than studies applied wet fatigue alone. Therefore, researchers are encouraged to utilise TC along with the mechanical cyclic loading whenever possible.
- ✓ Monolithic crown structure, CAD/CAM and pressed bi-layer crowns are better alternatives to hand-layered crowns especially when aesthetics is not of a concern.
- ✓ In-vitro fatigue testing protocols are highly variable across studies which introduce a need for international standardisation to allow for more valid

comparability of data. Thus, detailed reporting of results is recommended to help reader assess fractures and the possible clinical lifetime according to number of cycles.

2.7 Conflict of interest statement

Authors declare no conflict of interest.

2.8 References

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Linking page

The previous chapter (Chapter 2) provided a systematic review of the literature about the survival of both tooth-supported and implant-supported zirconia-based restorations in aqueous environment. It also highlighted all significance of the testing parameters used during in-vitro testing and their influence on the fracture strength of zirconia-based restorations.

The following chapter is the first of a series of experiments intended to examine the efficiency of implant-supported all-ceramic posterior crowns cemented to zirconia hybrid-abutments. It will examine and compare the fracture resistance of monolithic crowns made of two different all-ceramic materials; zirconia and lithium disilicate, when supported by implants. All-ceramic crowns in this study were made following the manufacturer recommendation for thickness and cemented to customised zirconia hybrid-abutments. The effect of chewing simulation will be discussed and differences between the two materials will be highlighted.

This chapter is accepted for publication in the Journal of Advance Prosthodontics and the bibliography is as follows:

Elshiyab S.H, Nawafleh N, Öchsner A, George R. Fracture Resistance of Implant-Supported Monolithic Crowns Cemented to Zirconia Hybrid-Abutments: Zirconia Crowns vs. Lithium Disilicate Crowns.

Chapter Three

**Fracture resistance of implant-supported monolithic
crowns cemented to zirconia hybrid-abutments:
zirconia crowns vs. lithium disilicate crowns**

Original research

(Accepted for publication)

STATEMENT OF CONTRIBUTION TO CO-AUTHORED PUBLISHED PAPER

This chapter includes a co-authored paper. The bibliographic details (if published or accepted for publication)/status (if prepared or submitted for publication) of the co-authored paper, including all authors, are:

Elshiyab S.H, Nawafleh N, Öchsner A, George R. Fracture Resistance of Implant-Supported Monolithic Crowns Cemented to Zirconia Hybrid-Abutments: Zirconia Crowns vs. Lithium Disilicate Crowns. This paper is accepted for publication in Journal of Advanced Prosthodontics.

My contribution to the paper involved: study protocol, experimental design and samples preparation, data collection, statistical analysis and preparation of the manuscript.

(Signed)

(Date) May 2017

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(Date) May 2017

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3.1 Abstract

Aims. The aim of this in-vitro study was to investigate the influence of chewing simulation on the fracture resistance of implant-supported posterior restorations (hybrid-abutment crown) made of different all-ceramic materials.

Materials and methods. Monolithic zirconia (MZr) and monolithic lithium disilicate (MLD) crowns for mandibular first molar were fabricated using Computer-Aided Design/Computer-Aided Manufacturing technology, and then cemented to zirconia hybrid-abutments (Ti-Based). Each group was divided into two subgroups (n=10); (A) control group, crowns were subjected to static load to fracture, (B) test group, crowns underwent chewing simulation using multiple loads for 1.2 million cycles, at 1.2Hz with simultaneous thermocycling between 5°C and 55°C. Data was statistically analysed with one-way ANOVA and a Post-Hoc test.

Results. All tested crowns survived chewing simulation resulting in 100% survival rate. However, wear facets were observed on all the crowns at the occlusal contact point. Fracture load of monolithic lithium disilicate crowns was statistically significantly lower than that of monolithic zirconia crowns. Also, fracture load was significantly reduced in both all-ceramic materials after exposure to chewing simulation and thermocycling. Crowns of all test groups exhibited cohesive fracture mode within the monolithic crown structure only, and no abutment fractures or screw loosening were observed.

Conclusions. When supported by implants, monolithic zirconia restorations cemented to hybrid-abutments should withstand molar masticatory forces. Also, fatigue loading accompanied by simultaneous thermocycling significantly reduces the load to fracture of both all-ceramic materials. Moreover, further research is needed to define potential,

limits and long-term serviceability of such combination of materials and hybrid-abutments.

3.2 Introduction

Implants are considered a successful treatment option for restoring one or multiple teeth in the oral cavity¹⁻⁴. However, when restoring a single tooth with a crown, osseointegration on its own is not sufficient for treatment success; the functional load-bearing capacity of the implant as well as the integration of the various components of the implant system including function and aesthetics, comprise the stamina in defining treatment success⁵⁻¹⁰. This combination of factors makes replacement of a missing tooth by an implant crown more challenging^{11,12}.

With the availability of Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) technology and the introduction of the high strength all-ceramic materials; the tendency towards replacing the metal-ceramic restorations with the highly aesthetic all-ceramic materials is increasing^{2,13-15}. Studies revealed no significant difference in survival between metal-ceramic and zirconia all-ceramic restorations¹⁶⁻¹⁸. While the use of some all-ceramic materials has been narrowed down mainly due to inaccurate fitting¹⁹; zirconia and lithium disilicate ceramics took over in recent years. Restorations made from these materials have demonstrated successful short and medium term survival rates under clinical performance²⁰⁻²⁶.

When choosing implant abutments, titanium has been the popular option for posterior region of the mouth because of its favourable mechanical properties^{27,28}. However, there is also a trend to substitute titanium abutments with all-ceramic materials i.e. Al_2O_3 and ZrO_2 ; to provide patients with a more aesthetically pleasing anterior or posterior restoration^{29,30}. Zirconia abutments were investigated in both in-vitro and in-vivo studies and showed both strength and biocompatibility needed for an abutment³¹⁻³⁴, and

often caused less plaque accumulation compared to titanium^{35,36}. In addition, zirconia abutments can be customised and fabricated using the CAD/CAM technology; adding simplicity, efficiency and reducing cost and time³⁷⁻³⁹.

The hybrid-abutment approach is a combination between strength and aesthetic together. However, it is still relatively new in implant dentistry. The all-ceramic hybrid-abutment crown system is made of three components: a) An all-ceramic crown, b) an all-ceramic abutment and, c) a Ti-Base abutment. It was first used in implant-supported prosthesis^{40,41}, and certain guidelines were proposed by Drago to ensure success of the hybrid-abutments⁴⁰. Clinical studies by Lin et al⁴² and Hornbrook⁴³ suggested the use of hybrid-abutments as an adequate approach to enhance aesthetic in the anterior region for single crowns using lithium disilicate.

Only few in-vitro studies have looked at the use of hybrid-abutments⁴⁴⁻⁴⁶ and their influence on the fracture resistance of all-ceramic crown^{44,45}. These studies showed that crown's structure (monolithic vs. bi-layered)⁴⁵, crown's all-ceramic material⁴⁵ and the abutment's material, abutment manufacturer and design⁴⁶, all have an influence on the fracture resistance of all-ceramic crowns. Monolithic zirconia crowns showed significantly greater strength compared to bi-layered zirconia-based crowns⁴⁵. Also, monolithic lithium disilicate crowns supported by lithium disilicate abutments with Ti-Base showed comparable results to all-metal abutment systems under fatigue⁴⁴.

Current literature provides only limited information on the fracture resistance of crowns supported by hybrid-abutments. There is currently no data available on the fracture resistance and post fatigue fracture load of all-ceramic crowns when supported by zirconia hybrid-abutments. Therefore, the aim of this study was to investigate fatigue resistance and post fatigue fracture load of all-ceramic crowns in hybrid-abutment system fabricated using different all-ceramic materials. This study adopted a clinically

relevant mechanical testing to investigate the influence of chewing simulation on the fracture resistance of implant-supported posterior restorations (hybrid-abutment crown). The hypothesis was that there would be no difference in fracture load between the tested zirconia and lithium disilicate crowns when cemented to zirconia hybrid-abutment and supported by dental implants. We also hypothesised that fatigue manifested by chewing simulation and thermal cycling, would have no significant effect on the fracture load of the tested all-ceramic materials.

3.3 Materials and methods

Forty Ankylos[®] implants (Ankylos[®] C/X, DENTSPLY–Friadent GmbH, Mannheim, Germany) with a diameter of 5.5 mm, and Internal Ankylos[®] compatible titanium base (Ti-Base) abutments (Dess, Dental Smart Solutions, Montcada, Spain) of 1.00 mm hex screw, 4 mm height and 0° angulations were used for this study. The forty implants were divided into two groups (n=20) according to the monolithic all-ceramic crown material to be tested; namely monolithic zirconia (MZr) and monolithic lithium disilicate (MLD).

3.3.1 Designing and milling of all-ceramic components (zirconia abutments and monolithic crowns)

CAD/CAM technology was used for the fabrication of both the zirconia abutments and the monolithic all-ceramic crowns (See Appendix 1). Using a dental laboratory scanner (3shape, Copenhagen, Denmark), Ankylos[®]ScanBase was scanned to obtain the Ti-Base geometry needed to design Zr abutments (Zenostar, Ivoclar Vivadent, Lichtenstein, Germany) with 1.0 mm depth shoulder.

With the split file technology, a monolithic crown was also designed according to manufacturer recommendations for minimum thickness of full contour crowns (1.0 mm gingival, 1.5 mm occlusal). The CAD file was transferred to a 5-axis milling machine

(ZENOTEC[®] select, Wieland Dental, Lindenstraße, Germany) to mill 40 Zr abutments and 20 MZr crowns using pre-sintered Zr discs (Zenostar Zr, Wieland Dental, Germany). A wet milling machine (ZENOTEC[®] select hybrid, Wieland Dental, Lindenstraße, Germany) was used to mill the 20 MLD crowns (IPS e.max[®] CAD for Zenotec, Wieland Dental, Germany). Zr structures (abutments & MZr) were sintered in a Programat S1[®] furnace (Ivoclar Vivadent, Schaan, Liechtenstein) (Figure 3.1), while MLD crowns were crystallised in a Programat EP 3010[®] furnace (Ivoclar Vivadent, Schaan, Liechtenstein). Upon completion of sintering and crystallisation, abutments and monolithic crowns were checked for fitting followed by glazing of all crowns as per manufacturer's instructions.



Figure 3.1. Sintering of Zr structures in a Programat[®] S1

3.3.2 Sample preparation for testing

To prepare the crowns for chewing simulation, specimen's holders were fabricated to ensure fitting to the chewing simulators' sample cup and to standardise the positioning of the implants across all the test groups (Figure 3.2). To position implants and create a negative replica of the sample cup; implants were screwed into a heavy putty (Coltene whaledent, Altstätten/Switzerland) to the desired perpendicular position to the horizontal plane up to the first thread to simulate clinical procedures. Afterwards, the negative replica with Ti-Base abutment screwed to implant were positioned in a cup and silicone duplicate material (Exaktosil N21, Bredent) was poured to create the positive replica of the sample cup, and was left to set in a pressure pot to avoid porosity. Finally, acrylic resin (Palapress vario, Heraeus Kulzer Wehrheim, Germany) was poured in the mold and upon setting was checked in the original chewing simulation sample cup for fitting. The base was made using acrylic resin; it has a modulus of elasticity of approximately 12 GPa which relatively approximates that of human bone (18 GPa)⁴⁷.

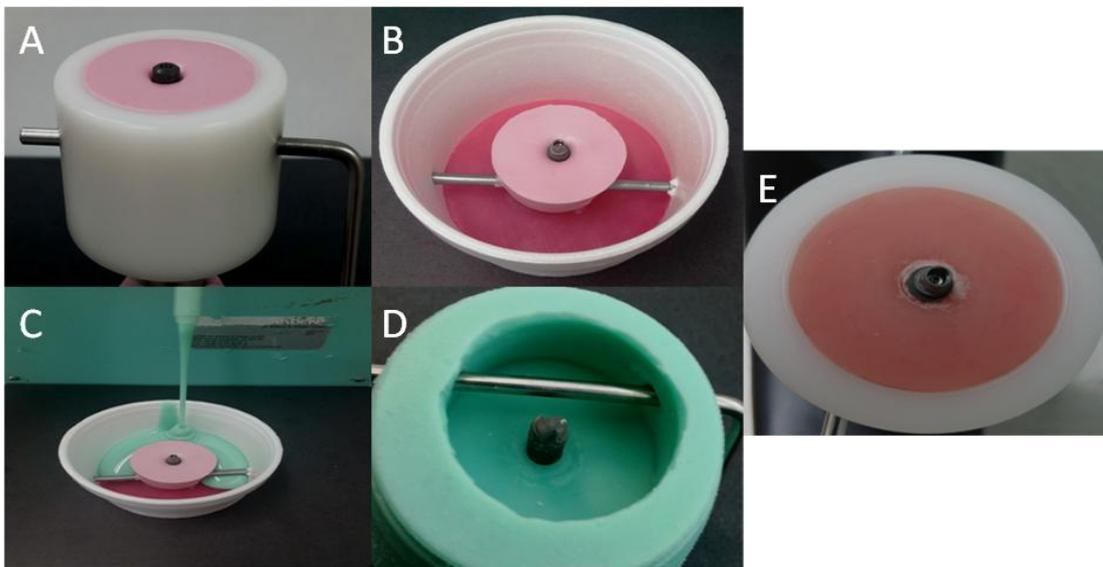


Figure 3.2. Fabrication of sample holder (A) Implant positioning and duplicating the CS sample cup to create a negative replica of the sample cup, (B & C) Creating the positive replica of the sample cup, (D) The positive sample cup replica with implant and Ti-Base (E)

3.3.3 Assembly of study components

To assemble all components, Ti-Base abutments were screw tightened on the implants with a torque wrench driver (Dentsply–Friadent GmbH, Mannheim, Germany) to 20 N/cm. The abutment access hole was filled with a temporary restorative material (Fermit N; Ivoclar Vivadent AG, Schaan, Liechtenstein). All Zr abutments were then cemented to the Ti-Base abutment using a self-curing dental luting composite (Multilink[®] Hybrid Abutment, Ivoclar Vivadent, Schaan, Liechtenstein) according to manufacturer instructions. Twenty-four hours later both MZr and MLD crowns were cemented to the Zr abutments using Multilink[®] Automix (Ivoclar Vivadent, Schaan, Liechtenstein) according to manufacturer instructions. All specimens were stored at 37°C in distilled water for a minimum of 7 days prior to testing; to ensure overall hydration of both the cement and the embedding material⁴⁸.

Each group was divided into two subgroups (n=10); a) control group, crowns were subjected to static load to fracture (SLF) using a universal testing machine (Model LRX; Lloyds Instrument, West Sussex, UK) and b) crowns underwent fatigue by means of chewing simulation (CS) (CS-4.8; SD Mechatronik GmbH, Feldkirchen-Westerham, Germany) for 1.2 million cycles prior to the SLF test.

3.3.4 Fracture resistance testing

3.3.4.1 *Chewing simulation and thermocycling*

Crowns underwent CS for 1,200,000 cycles with a 6-mm diameter stainless steel spherical indenter, according to the following protocol; 50 N for 250,000 cycles, followed by 100 N for 500,000 cycles and finally 50 N for another 450,000 cycles with a loading frequency of 1.2 Hz. This loading protocol equates to 5 clinical years; corresponding to previous studies, 250,000 cycles were used to simulate one year of clinical service⁴⁷. To simulate natural masticatory function, articulating paper was used

to position indenters 0.5 mm lingual to the disto-buccal cusp tip and sliding 0.3 mm lingual⁴⁹ to the central fossa with a mouth opening of 6 mm. During testing, each crown was subjected to simultaneous thermal cycling between 5°C and 55°C in distilled water resulting in 5118 thermal cycles with 60 s dwell time for each cycle and 15 s pause time to empty the chambers. Each crown was checked for any cracks, chipping or fractures at the end of each loading stage using an endodontic optical microscope at 12X (GLOBAL A-Series™, Global Corp., MO, USA).

3.3.4.2 *Static load to fracture*

A jig with a sample cup similar to that of the chewing simulator was specifically designed for the SLF testing (Figure 3.3a); to ensure stability of samples during testing. All crowns of the control group as well as those survived CS were then subjected to SLF test in the universal testing machine (Lloyds Instrument Model LRX, Fareham, England). Load was vertically applied with 0° angulation at the triangular ridges of both lingual cusps and the disto-buccal cusp using 6-mm diameter spherical stainless steel indenter at a crosshead speed of 1 mm/min⁵⁰ until failure (Figure 3.3b). Articulating paper was used to ensure indenters' position is standardised across all tested crowns. The fracture load for SLF test of all the groups was recorded in Newton (N).



Figure 3.3. (A) A jig especially designed for SLF testing (B) Position of indenter during SLF testing

3.3.5 Scanning Electron Microscopy

One crown from each group was randomly selected to be examined using Scanning Electron Microscopy (SEM) (Jeol, JCM-5000 NeoScope™, Tokyo, Japan) to evaluate fractured surfaces. Crowns were sputter coated with gold (Leica EM SCD050, Wetzlar, Germany) to a thickness of approximately 15 μm prior to imaging.

3.3.6 Statistical analysis

Data was analysed using the SPSS statistical software (version 22.0; IBM, Chicago, USA). All-ceramic material and testing regimes as well as the loads at fracture for each group were registered and descriptive statistics (mean and standard deviation (SD)) was performed. To evaluate statistical significance between groups a one-way analysis of variance (ANOVA) was conducted, followed by LSD Post-Hoc test. All the statistical analysis was performed with significance level set at 5% (two-tailed).

3.4 Results

This study showed that all crowns (MZr and MLD) survived the CS testing resulting in 100% survival rate. However, wear facets were observed in all crowns at the occlusal contact point (Figure 3.4).



Figure 3.4. Wear facets visible on the disto-buccal cusp of tested crowns after CS (arrows) using an endodontic microscope at 12x; (A) MZr (B) MLD

Fracture load mean and SD of all groups are presented in figure 3.5. Generally, fracture load means of MLD crowns were lower than that of the MZr group. Among each ceramic group, the unfatigued crowns had higher fracture load mean than that of the fatigued crowns; the mean fracture load of the MZr control group was 3929.5 ± 491.4 compared to 3131.5 ± 714.1 of the fatigued group. While MLD control group and fatigued MLD recorded mean fracture loads of 2077.4 ± 99.6 and 1646.2 ± 211 respectively.

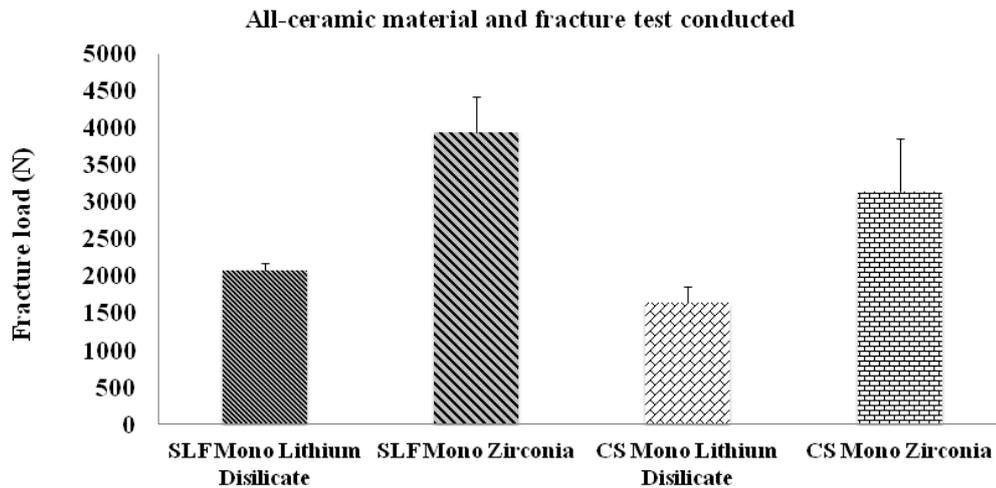


Figure 3.5. Mean and standard deviation of fracture load in Newtons for MZr and MLD

One-way ANOVA analysis showed significant differences between MZr and MLD groups and within the subgroups. LSD Post-Hoc tests showed significant difference in fracture load between the MZr control and MLD control $p \leq 0.05$. Within each ceramic group, significant differences were present between the control group and the fatigued group; $p \leq 0.05$ in both MZr and MLD groups.

Both MZr and MLD crowns exhibited cohesive fracture mode within the monolithic crown structure only. Both materials showed different fracture path with different number of fracture fragments (Figure 3.6). None of the zirconia abutments fractured upon completion of SLF testing of both groups.

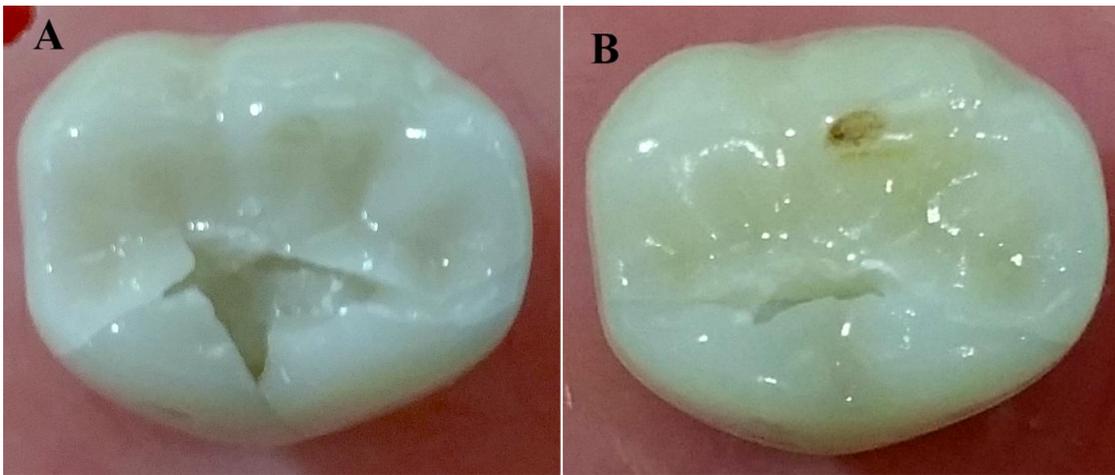


Figure 3.6. Fracture path for the two tested groups after SLF (A) MZr; 3 pieces fracture along the mesiodistal plane and the lingual developmental groove (B) MLD; 2 pieces fracture along the mesiodistal plane

SEM imaging showed the presence of hackles in both MZr and MLD fractured surfaces, which indicates the orientation of crack as shown in figure 3.7.

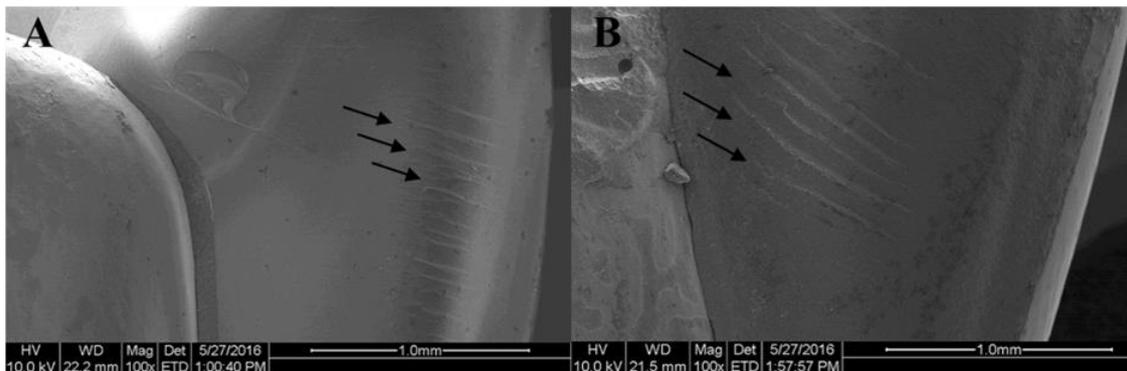


Figure 3.7. Representative SEM images after fracture resistance testing showing hackles in both (A) MZr, (B) MLD

3.5 Discussion

This study focused on implant-supported restorations using the hybrid-abutment concept⁴⁰⁻⁴³. It investigated the influence of chewing simulation on the fracture resistance of all-ceramic crowns made of two different materials (zirconia and lithium disilicate) in the posterior region. Results of this study showed that implant-supported monolithic crowns made of zirconia had significantly higher fracture resistance

compared to the monolithic crowns made of lithium disilicate material. The results also suggest that fatigue application caused significant reduction in the fracture resistance of both all-ceramic groups. These findings reject the null hypothesis stated that there will be no significant difference in fracture load and fatigue resistance between monolithic zirconia and lithium disilicate implant-supported crowns used in combination with zirconia abutment cemented to Ti-Base.

To author's knowledge, this work is the first to report on this combination of materials, designs and testing protocol in an in-vitro context. Therefore, comparing the findings of the current study to the findings of current published work should be made with caution mainly because of the differences in the combinations of materials, system and the geometry.

Prior to releasing a material for clinical use, in-vitro tests are necessary to prove materials' performance and applicability. Such tests can be performed in a short period of time with a standardised test parameters⁵¹, and its results are more clinically relevant when the tests conducted closely simulate the clinical conditions⁵². Mastication devices can closely simulate clinical mastication loading (ML) present in the oral environment^{51,52}, including the force amount, frequency and temperature fluctuation by means of thermocycling (TC)⁵³.

The current study tested the all-ceramic crowns before and after fatigue by means of chewing simulation and sliding contact motion was applied. Due to the nature of the mechanical fatigue which ceramic materials undergo in the oral cavity, fatigue testing would be a more representative testing approach⁵⁴. Also, axial contact rarely happens in the clinical situation; therefore, sliding contact is always the best to clinically simulate the chewing cycle in the oral cavity⁵⁵.

Our results confirm that chewing simulation over 5 years had an impact on the fracture strength of different all-ceramic hybrid-abutment crown systems when supported by an implant. Mechanical stress and wet environment together “hydrothermal stress” in particular, can accelerate the aging of zirconia structures. Aging of zirconia also termed as “low temperature degradation” (LTD)⁵⁶⁻⁵⁸, is a phenomenon where crystals slowly transform from the stable tetragonal phase to the less stable monoclinic phase in the absence of any mechanical load^{59,60}. Various factors cause aging, such as grain size⁶¹, residual stress as well as stabilizer type and content⁵⁹. Surface defects, processing and finishing techniques as well as vapour and temperature also play a key role in aging of any zirconia structure^{60,62,63}.

Due to the blanks material properties and their geometry, monolithic crowns milled from zirconia perform well when used in the molar region and supported by implants⁶⁴. de Kok et al reported that were only SLF was used, the highest load to fracture was observed for monolithic zirconia crowns, followed by lithium disilicate crowns when cemented to a prefabricated titanium abutment⁶⁵. When monolithic crowns made of zirconia and lithium disilicate were compared, zirconia was also superior to lithium disilicate in terms of fracture strength^{64,66}. The present study showed that monolithic zirconia restorations had significantly higher fracture resistance compared to monolithic lithium disilicate crowns. Kelly (2004) reported that strong highly crystalline ceramics have more opaque appearance and less translucency compared to aesthetic ceramics⁶⁷. It is also known that, ceramic materials strength declines when exposed to mechanical loading; this usually cause subcritical crack propagation initiated by humid environment of the artificial mouth imitating the oral environment⁶⁸.

Using zirconia as an abutment material for implant-supported restorations has proven to be superior to other all-ceramic materials; an in-vitro study⁶⁹ on the fracture resistance

of all-ceramic restorations on implants revealed that crowns supported with ZrO_2 abutments withstood higher load to fracture than those supported with Al_2O_3 abutment. Clinically, a 4-year result of a prospective clinical study, reported that abutments made of zirconia can provide enough stability to support single-tooth restorations in anterior and premolar regions when supported by implants, and that showed very well response to both the soft and hard tissues³¹. Similarly, a systematic review by Sailer et al⁷⁰ have reported a high cumulative success rate of zirconia implant abutments after 11-year follow up, in both the anterior and the posterior regions.

A recent 2016 study on implant-supported monolithic crowns reported that lithium disilicate crowns had generally a higher fracture resistance value after thermocycling mechanical loading (TCML) compared to polished zirconia reinforced lithium silicate crowns. However, the difference in fracture force values was not statistically significant. Nevertheless, Straumann implant-abutment dummies were used in this study rather than zirconia abutments⁷¹.

Two in-vitro studies on hybrid-abutments were recently published^{44,46}. Silva et al⁴⁴ tested lithium disilicate hybrid-abutment in the anterior region; the ceramic crown and the lithium disilicate abutment on the Ti sleeve were concluded to be clinically reliable, however, success was limited by the abutment screw. Similarly, Kelly et al studied the hybrid-abutments in the anterior region; zirconia abutments were tested against zirconia hybrid-abutments⁴⁶. The load was directed on the abutments and no crowns were involved in the testing. Hence, the results of both studies cannot be compared to the results of the current study.

None of the abutment screws fractured upon completion of the static load to fracture testing. However, with regard to the failure observed in this study, crowns made of both zirconia and lithium disilicate failed predominantly by bulk fracture involving the whole

thickness of the crown. This mode of fracture is the most common mechanical failure in LD restorations reported in previous in-vivo⁷²⁻⁷⁴ and in-vitro studies^{54,75-77}. In a clinical context, radial cracks from the cementation surface, propagates toward the occlusal surface and cause bulk fracture of dental crowns^{52,78-80}. However, in laboratory simulation, bulk fracture mostly results from it is the extension of Hertzian cone cracks which cause the bulk fracture; they extend from the surface underneath the loading indenter and propagate to the whole crown thickness⁷⁶. A previous in-vitro study⁵⁴ demonstrated that radial cracks at the cementation surface beneath the contact point did not occur until the cyclic loading force was increased to 1400 N. Therefore, the loading forces used during the cyclic loading in this study were not enough to generate radial cracks.

3.6 Clinical implication

Although suggested by Lin et al⁴² and Hornbrook⁴³ as an adequate approach in restoring teeth supported by implants, there is currently little scientific information and clinical data on the applicability of hybrid-abutment concept in specific and implant-supported restorations⁸¹ in general. Hence, the current study provides practitioners with evidence for choosing the designs and materials to protect the benefit of their patients and potentially provide manufacturers with feedback regarding processing and design issues.

3.7 Limitation

While enamel would be considered the ideal material to be used as an antagonist for in-vitro testing of restorative materials; the use of a spherical stainless steel indenter instead of natural tooth as an antagonist during the cyclic loading might be considered a limitation in this study. However, natural teeth vary in morphology and require a precise machining process for manufacturing which makes it less convenient and accurate⁸².

Also, using sphere antagonist in the in-vitro cyclic loading testing was considered a good and adequate approach to understand the clinical flaw mechanism, however hard to predict⁸³.

3.8 Conclusions

Within the limitation of the current study, the following was concluded:

1. Implant-supported monolithic zirconia restorations cemented to hybrid-abutments are unlikely to fracture and should have satisfactory clinical performance withstanding molar masticatory forces.
2. Despite the different aging process which occurs in both zirconia and lithium disilicate crown materials; however, fatigue loading with simultaneous thermocycling caused aging in both tested materials and reduced their strength significantly.
3. Clinical trials are important to provide the final word in the applicability of the hybrid-abutment concept, and current data is not sufficient yet to suggest a safe clinical serviceability. Therefore, further research is needed to define potential, limits and long-term serviceability of such combination of materials and hybrid-abutment system.

3.9 Acknowledgments

The authors would like to thank Ivoclar Vivadent for providing study materials. Also, grateful for Mrs. Helen Monaghan and Mrs. Kylie Mortimer from the School of Dentistry and Oral Health at Griffith University for facilitating prosthodontic laboratory resources during the preparation of study samples. Also, would like to thank Mr. Ian Underhill from School of Engineering at Griffith University for his help in the mechanical testing.

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Linking page

The previous chapter highlighted the significance differences in fracture resistance of both zirconia and lithium disilicate hybrid-abutment crowns when supported by implants.

The following chapter (chapter 4) was formatted as a journal article and is currently under review by a peer reviewed journal. This study compared the fracture resistance and in-vitro survival of zirconia-based hybrid-abutment crowns fabricated in two structural forms (mono-layer and bi-layer).

The bibliography is as follows:

Elshiyab S.H, Nawafleh N, Walsh L, George, R. Fracture Resistance and Survival of Implant-Supported Zirconia-Based Hybrid-Abutment Crowns: Influence of Aging and Crown Structure. The paper is submitted for publication.

Chapter Four

Fracture resistance and survival of implant-supported zirconia-based hybrid-abutment crowns: influence of aging and crown structure

Original research paper

(Submitted for publication)

STATEMENT OF CONTRIBUTION TO CO-AUTHORED PUBLISHED PAPER

This chapter includes a co-authored paper. The bibliographic details (if published or accepted for publication)/status (if prepared or submitted for publication) of the co-authored paper, including all authors, are:

Elshiyab S.H, Nawafleh N, Walsh L, George, R. Fracture Resistance and Survival of Implant-Supported Zirconia-Based Hybrid-Abutment Crowns: Influence of Aging and Crown Structure. Paper is submitted for publication.

My contribution to the paper involved: study protocol, experimental design and samples preparation, data collection, statistical analysis and preparation of the manuscript.

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4.1 Abstract

Objectives. To investigate the fracture resistance of aged zirconia-based crowns (mono-layer zirconia vs. bi-layer) supported by implants and cemented to hybrid-abutments.

Materials and methods. Crowns of mono-layer zirconia (MLZ) and bi-layer zirconia (BLZ) for lower molar were constructed as per manufacturer instructions. Crowns were cemented to zirconia hybrid-abutments and groups were divided into; control group (Non-aged; n=10) subjected to static load to fracture and test group (Aged; n=10) underwent thermal cycle mechanical loading (TCML). Cyclic loading up to 1.2 million cycles was achieved with controlled temperature fluctuation between 5°C and 55°C. Fractured surfaces of randomly selected crowns from each group were observed under scanning electron microscopy. Data was analysed for normality and then assessed using one-way ANOVA and T-test.

Results. MLZ crowns had 100% survival rate upon completion of TCML while BLZ crowns had 50% survival rate; crowns failed (chipped) at different number of cycle. Statistics showed that fracture load of MLZ crowns was significantly higher than that of BLZ crowns. Moreover, fracture load was significantly reduced in MLZ crowns after aging. MLZ crowns had bulk fracture within the monolayer; while BLZ crowns exhibited cohesive fracture mode within the veneering porcelain and no frameworks fractured. No implant neither abutment fractures or screw loosening was seen.

Conclusions. Mono-layer Implant-supported hybrid-abutment crowns exhibit significantly higher fracture resistance compared to bi-layer crowns; mono-layer crowns can withstand the higher masticatory loads in the posterior region. Also, mechanical loading and aging significantly reduce resistance to fracture and survival of both crown structures.

4.2 Introduction

Zirconia have been used as a crown and as an implant abutment material to substitute titanium for preferable aesthetics¹⁻⁵. When supported by implants, zirconia crowns can either be manufactured using a mono-layer (monolithic) or a bi-layer technique.

Despite the evidence of zirconia crowns being able to withstand masticatory loads in the oral cavity; veneer chipping has often been clinically reported^{2,6-15}. Interestingly, chipping rate in implant-supported crowns was higher than that of tooth-supported crowns^{16,17}. This could be related to the rigid implant abutment material used in the implant-supported crowns^{18,19}, and the absence of periodontal ligaments around the implant^{20,21}.

In spite of attempts to improve the strength of zirconia-based crowns by using the yttria-stabilized tetragonal zirconia polycrystal²²; bi-layer crowns were still reported to have higher chipping rate than monolithic crowns^{17,23}. Core-veneer interface in the bi-layer crowns are reported to be the primary area of chipping of the layered porcelain^{12,24}. In addition, factors such as framework design, thermal stresses during firing²⁵ and mechanically weak porcelain can also limit the strength of the crown and lead to veneer chipping^{23,26}. The introduction of aesthetically pleasing translucent tooth-coloured zirconia to dental industry has allowed for the fabrication of crowns without veneering (mono-layer); a more feasible option^{27,28} that could prevent chipping. However, the chemical stability of these restorations can be compromised by moisture and low thermal/temperature degradation (LTD) or what's so called aging^{29,30}.

During service in the oral cavity phase transformation might occur and the zirconia-based crowns might undergo crack propagation due to the presence of saliva and the continuous stress caused by the mastication forces³⁰. The aim of this study was to evaluate the fracture resistance of aged zirconia-based crowns (mono-layer zirconia vs.

bi-layer) supported by implants and cemented to a hybrid-abutment. The null hypothesis was that the crown structure (mono-layer or bi-layer) would have no influence on the fracture resistance of zirconia-based hybrid-abutments crowns supported by dental implants. We also hypothesised that fatigue and aging caused by TCML, would also have no significant effect on the survival of mono-layer and bi-layer all-ceramic structures.

4.3 Materials and methods

4.3.1 Crowns preparation

For the purpose of this study, anatomically correct crowns for mandibular first molar were fabricated, cemented to zirconia abutments and allocated to two groups according to crown build structure, namely: mono-layer zirconia crown structure (MLZ) and bi-layer zirconia structure (BLZ). Zirconia abutments were cemented to Ankylos[®] compatible titanium base (Ti-Base) abutments (Dess, Dental Smart Solutions, Montcada, Spain) of 1.00 mm hex screw, 4 mm height and 0° angulations which were torqued to Ankylos[®] implants (Ankylos[®] C/X, DENTSPLY–Friadent GmbH, Mannheim, Germany of 5.5 mm diameter).

To obtain the Ti-Base geometry required for designing the zirconia abutments; a scan base (Ankylos[®] ScanBase) was scanned using a dental laboratory scanner (3Shape, Copenhagen, Denmark). Using the split file technology required for designing a crown and abutment together; zirconia abutments had 1.0 mm depth shoulder. Mono-layer zirconia crowns (1.3 mm circular and fossa line, and 1.5 mm cusps height) were designed as per the manufacturer's recommendation of minimum thickness. In addition, zirconia frameworks (0.6 mm circular and 0.7 occlusal) were anatomically designed in a separate file in accordance with manufacturer's recommendations of minimum thickness (See Appendix 1).

All the above mentioned design files; zirconia abutments, anatomical framework and mono-layer zirconia crowns were then transferred to 5-axis milling machine (ZENOTEC[®] select, Wieland Dental, Lindenstraße, Germany) and milled from pre-sintered zirconia discs (Zenostar, Ivoclar Vivadent, Lichtenstein, Germany). Afterwards, zirconia structures were sintered to full density in the recommended Programat S1[®] furnace (Ivoclar Vivadent, Schaan, Liechtenstein) and left to slow cool at room temperature. Zirconia abutments, mono-layer zirconia crowns and zirconia frameworks were checked for fitting. Finally, MLZ crowns were glazed as per the manufacturer's instructions. Manufacturer reported physical properties of the ceramic crown materials tested indicate greater flexural strength and fracture toughness values for Zenostar compared to IPS e.max Ceram^{31,32}.

For the BLZ crowns, hand layering of zirconia frameworks was made by a dental technician with 25 years of experience using IPS e.max Ceram Dentin and Enamel (Ivoclar Vivadent, Schaan, Liechtenstein) as the layering porcelain. Silicone indexes were used to ensure standardisation of both thickness and anatomical shape of the layering porcelain on BLZ crowns. Firing conditions for BLZ crowns are listed in table 4.1.

Table 4.1 Firing conditions for BLZ crowns

	ZirLiner firing	Wash firing	1st/2nd Dentin/ Incisal firing	Glaze firing
Stand-by temperature B (°C)	403	403	403	403
Closing time S (min)	04:00	04:00	04:00	06:00
Temperature increase t (°C/min)	40	90/20	90/20	60
Holding temp T (°C)	960	650/730	650/730	725
Holding time H (min)	01:00	00:00/02:00	00:00/02:00	01:00
Vacuum 1 V1 (°C)	450	400/650	400/650	450
Vacuum 2 V2 (°C)	959	650/729	650/729	724
Long-term cooling L (°C)	off	off	off	450
Cool down gradient tl (°C)	off	off	off	off

To assemble study samples for testing, the Ti-Base abutment access hole was filled with a temporary restorative material (Fermit N; Ivoclar Vivadent AG, Schaan, Liechtenstein). Zirconia abutments were then cemented to the Ti-Base abutment using a self-curing dental luting composite (Multilink[®] Hybrid Abutment, Ivoclar Vivadent, Schaan, Liechtenstein) according to manufacturer instructions. Twenty-four hours later both MLZ and BLZ were adhesively luted to the zirconia abutments using Multilink[®] Automix (Ivoclar Vivadent, Schaan, Liechtenstein) following the manufacturer instructions. All specimens were stored at 37°C in distilled water for 7 days prior to testing; to ensure overall hydration of both the cement and the embedding material³³.

At this stage each MLZ (n=20) and BLZ (n=20) groups were divided into two subgroups (n=10) according to the mechanical testing to be conducted; 1) control group; non-aged crowns but subjected to static load to fracture (SLF) 2) test Group; aged crowns by means of TCML prior to SLF test.

4.3.2 Aging and Mechanical testing

To prepare the crowns for TCML, specimen's holders were fabricated by creating a replica of the chewing simulator's sample cup. All implants were embedded in acrylic resin base (Palapress vario, Heraeus Kulzer Wehrheim, Germany) up to the first thread to simulate clinical procedures; acrylic resin has a modulus of elasticity of approximately 12 GPa which approximates that of human bone (18 GPa)³⁴. Also, special jig was designed for the SLF test (Figure 4.1) to fit the TCML samples and to ensure that samples are stable during compressive loading.

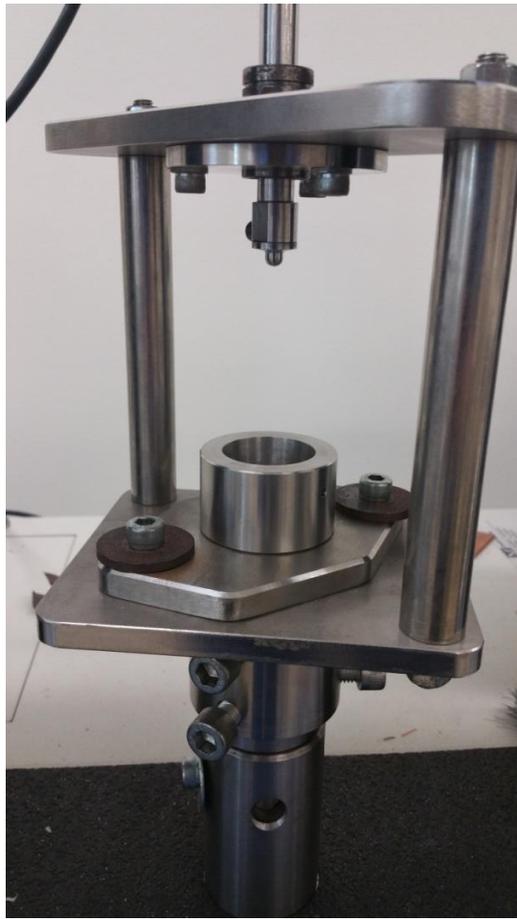


Figure 4.1. Special jig made for static load to fracture testing to fit TCML samples

4.3.2.1 Thermal cycling mechanical loading

Crowns underwent 1,200,000 cycles of mechanical loading (CS-4.8; SD Mechatronik GmbH, Feldkirchen-Westerham, Germany) using a 6-mm diameter stainless steel spherical indenter. This number of cycles should simulate 5 years of clinical service; corresponding to previous studies³⁴⁻³⁶, were 250,000 cycles were used to simulate one year of clinical service. Crowns were initially loaded with 50 N for 250,000 cycles, followed by 100 N for 500,000 cycles and finally 50 N for another 450,000 cycles with a loading frequency of 1.2 Hz. Articulating paper was used to position indenters 0.5 mm lingual to the disto-buccal cusp tip and sliding 0.3 mm lingually³⁷ toward the central fossa with a mouth opening of 6 mm. This setting is proposed to simulate aspects of natural masticatory function³⁸ (Figure 4.2). Throughout the testing, each crown was subjected to simultaneous thermal cycling between 5°C and 55°C in distilled water

(5118 thermal cycles, 60 s dwell time, and 15 s pause time to empty the chambers). Using an endodontic optical microscope GLOBAL A-Series™, Global Corp., MO, USA), each crown was inspected, at the end of each loading stage, for cracks, chipping or fractures that might have occurred during that particular loading stage. If any chipping or crack was observed, the corresponding crown was removed from further TCML testing.

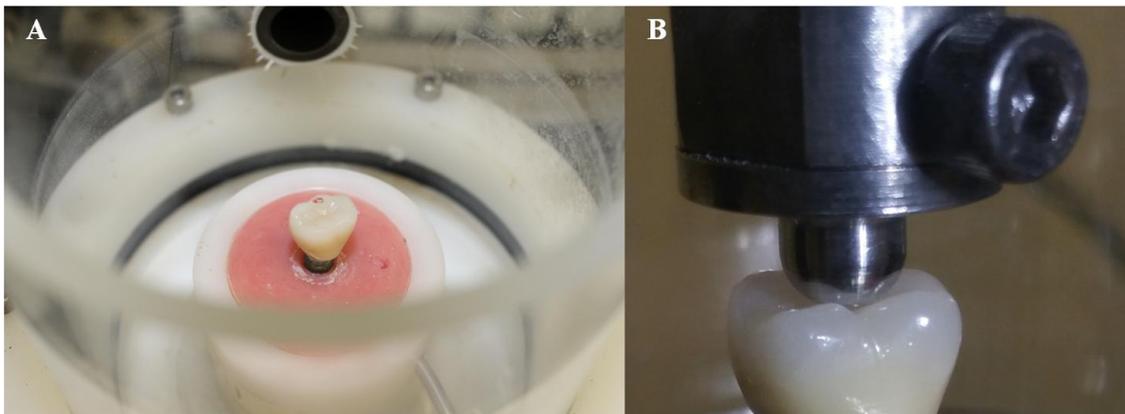


Figure 4.2. A) Indenter location during TCML testing (articulating paper mark on the distobuccal cusp)
B) Indenter location during SLF testing

4.3.2.2 *Static load to fracture*

Crowns of the control groups as well as those survived TCML were then subjected to compressive SLF test until failure in a universal testing machine (Instron, Model 3367, Massachusetts, United States) (Figure 4.2). To check any difference between the BLZ crowns that failed during TCML and the ones that survived, failed crowns were subjected to SLF until bulk fracture. A 6-mm diameter sphere stainless steel indenter was used to apply compressive loading on the crowns at three point's contact which consisted of the triangular ridges of both lingual cusps and the disto-buccal cusp at a crosshead speed of 1 mm/min³⁹.

4.3.3 Scanning Electron Microscopy

To assess fractured surfaces and mark differences between all the aforementioned groups, a crown from each group was randomly selected to be observed using TESCAN Scanning Electron Microscopy (SEM) (Mira 3XMU, Kohoutovice, Czech Republic). Crowns were sputter coated with gold (Leica EM SCD050, Wetzlar, Germany) to a thickness of approximately 10 µm prior to imaging.

4.3.4 Statistical analysis

SPSS statistical software (version 24.0; IBM, Chicago, USA) was used for this study analysis. Data was analysed for descriptive data and then assessed for normality (Skewness and Kurtosis tests as well as against P-P Plots). Means of the four subgroups were compared using One-Way ANOVA followed by Tukey HSD post-hoc test to determine significance between fracture loads of all the subgroups. Fracture load data of crowns in BLZ subgroup which survived TCML was further analysed against the survived crowns using T-Test. All the statistical analysis was performed with significance value percent set to 95.

4.4 Results

4.4.1 Thermal cycling mechanical loading

Neither MLZ crowns nor implants fractured during TCML in the chewing simulator, and no evidence of fractures and/or cracks was observed. However, five of the BLZ crowns failed during TCML under the indenter loading point and at different number of TCML cycles (Table 4.2, Figure 4.3); resulting in 50% survival rate.

Wear facets were observed in both MLZ and the remaining BLZ crowns at the indenter contact point at the end of TCML; however, this was not assessed further as this was not the focus of this study.

Table 4.2 Data of failed BLZ crowns during TCML

Failed BLZ during TCML	Load (N)/ Stage	Mechanical Loading Cycle	Number of Thermal Cycle	Fracture Load (N) after TCML
Crown # 1	50/ 1	250.000	1058	511
Crown # 2	50/ 1	250.000	1058	603
Crown # 3	100/ 2	418.000	2845	774
Crown # 4	100/ 2	500.000	3195	780
Crown # 5	100/ 2	500.000	3195	809



Figure 4.3. Chipping location of BLZ during TCML at the distobuccal cusp

4.4.2 Static load to fracture

Results of the fracture load testing are presented in table 4.3. Normal distribution of data was confirmed by Skewness and Kurtosis as well as the P-P Plots. The mean fracture loads of MLZ sub-groups were higher than that of BLZ sub-groups. Also, among each group, non-aged crowns had a maximum fracture load higher than that of aged crowns.

Table 4.3 Fracture load data (N) of study groups

Group		Number of crowns	Mean	Standard deviation	Standard error	Minimum	Maximum	
MLZ	SLF	10	3929	491	155	3348	4796	
	TCML	10	3131	714	226	2071	4481	
BLZ	SLF	10	1469	130	41	1258	1640	
	TCML	Failed	5	696	131	59	511	809
		Survived	5	1144	66	30	1096	1258

One-way ANOVA analysis showed significant differences between groups ($p < 0.05$). Tukey HSD post-hoc tests showed that non-aged MLZ crowns had significantly higher fracture load than both non-aged and aged BLZ ($p < 0.05$). Within MLZ group, non-aged crowns also had significantly higher fracture loads compared to aged crowns ($p < 0.05$). However, fracture load was not statistically significantly different between BLZ non-aged and aged subgroups. Using the T-test to compare failed and survived crowns of the aged BLZ subgroup, it showed a significant difference of fracture load between both subgroup ($p < 0.05$).

MLZ crowns failed by bulk fracture throughout the whole thickness of the crown; crowns fractured into 3 pieces along the fossa line to the mesiodistal plane and the lingual developmental groove in both subgroups. Nevertheless, BLZ crowns had a cohesive fracture of the veneering on the lingual cusps which extended to the interface with the framework (Figure 4.4) and no framework fractured occurred. It is worth mentioning that no abutments or implants were fractured and no screw loosening occurred in any of the study groups.



Figure 4.4. Representative images of fracture path after SLF for A) MLZ crown B) BLZ crown survived TCML C) BLZ crown failed during TCML

4.4.3 Scanning Electron Microscopy

Representative SEM images of fractured surfaces are presented in figure 4.5. Presence of pores in the veneering layer was evident (Figure 4.5.B&C). Hackle lines were also present on crowns of both MLZ and BLZ fractured surfaces, which indicates the orientation of crack.

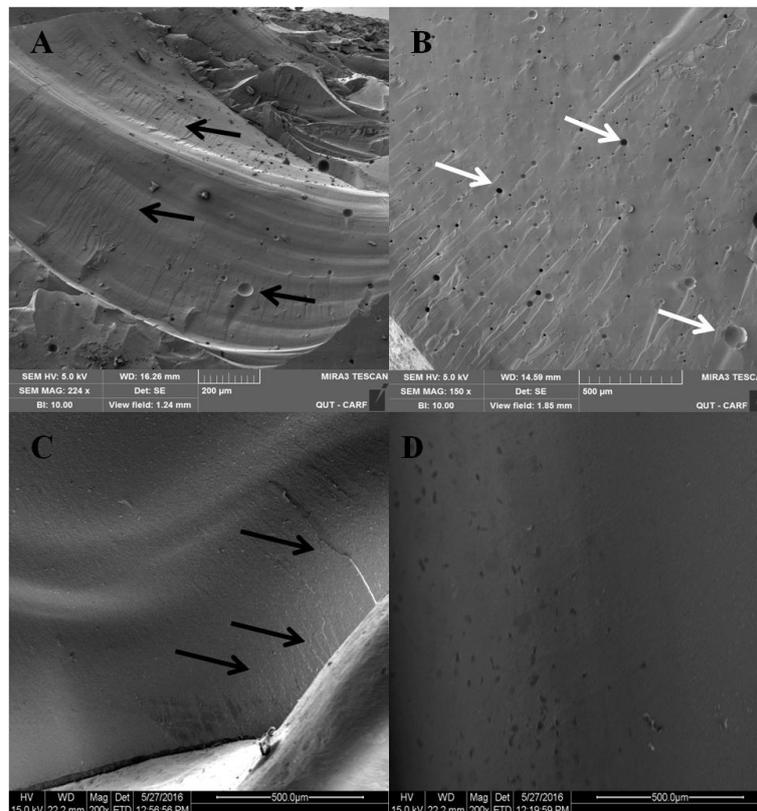


Figure 4.5. Representative SEM images of fractured surfaces (A) BLZ fractured surface under the loading indenter at 224x showing hackles (B) pores were clear in the veneering layer at 150x (C) MLZ fractured surface at 200x showing hackles lines (D) other than remains of the ceramic material upon fracture; no pores were observed in the mono-layer crown layer at 200x

4.5 Discussion

The current study focused on zirconia-based implant-supported hybrid-abutment crowns fabricated in two different structures; mono-layer vs. bi-layer in the posterior region. Results of this study showed that mono-layer hybrid-abutment crown structure had significantly higher fracture load compared to the bi-layer. The results also suggest that aging and mechanical loading caused significant reduction in fracture resistance of mono-layer zirconia crowns. Nonetheless, the same cannot be said about the bi-layer crowns where significant difference was only present between the survived and failed crowns of the aged subgroup when subjected to static load to fracture. These findings decline the null hypothesis that there would be no significant difference in fracture resistance or survival between the two investigated hybrid-abutment crown structures. In addition, the hypothesis that aging and mechanical loading together will have no significant effect the survival of all-ceramic structures was also rejected for the mono-layer hybrid-abutment zirconia crowns. To the author's knowledge, work conducted in this study (the combination of testing protocol and the use of hybrid-abutment crowns) has no similarity in the literature neither in the in-vivo nor in-vitro perspective. Hence, results of this study maybe difficult to be directly compared to other studies.

A previous in-vitro study evaluated the fracture load of different zirconia based crowns⁴⁰; bi-layer zirconia crowns had significantly lower fracture loads than the mono-layer crowns, which agree with the results of the current study. However, the aforementioned study³⁸ tested material under compressive axial loads only and none of the crowns underwent TCML. Other studies^{41,42} provided similar results; where fracture load of mono-layer zirconia crowns exceeded 3000 N.

A high translucent zirconia was used in this study. The bi-layer crown structures had lower fracture loads compared to mono-layer zirconia crowns. These types of highly

translucent bi-layer zirconia crowns will show higher fracture load values compared to the low translucent counterparts, due to the higher toughness of the more translucent zirconia and the adhesion of the veneering ceramics⁴³.

In general, implant-supported restorations and fixed dental prosthesis (FDPs) have higher risk of technical complications such as veneer chipping, due to the lack of the periodontal ligaments which provide shock absorption response during mastication loads⁴². This subjects the restorations to undue mastication loads causing such technical failures to occur. However, it is important to consider that the resulting fracture loads in the aforementioned study⁴⁴ and in this study (over 3000 N even after TCML) are still higher than the maximum posterior masticatory forces reported in the literature, which is expected to be around 700-900 N⁴⁵⁻⁴⁸. This suggests that they can provide acceptable clinical outcomes and are indeed able to withstand the molar masticatory forces.

SLF for bi-layer crowns that survived TCML exceeded 1000 N. Bi-layer crowns that did not survive TCML suffered chipping during the first and second clinically simulated year, and generally recorded low fracture load values (Table 4.1). This agrees with both lab studies and clinical reports where chipping of the veneer in the bi-layer zirconia-based crowns is the most frequently reported drawback of the material, especially in the hand-layering technique⁴⁹⁻⁵³. Framework design, properties of the veneering material and the processing technique⁵⁴, bond between the framework and veneer, have all been proposed to be factors that may influence the success of bi-layer structures. Nonetheless, no evidence supporting one over another has been suggested.

Anatomically designed frameworks were used for this study; as ceramic materials are brittle and bounded to limited ability to absorb tensile energy; the presence and the distribution of tensile stresses may influence the material's behaviour and cause weakness leading to early failure under low functional stress loads⁵⁵⁻⁵⁷. Therefore, an

appropriately designed anatomical framework will provide support to the veneering porcelain to prevent tensile forces within the porcelain and allows for durability to mastication loads during function^{58,59}.

Strength of the veneering ceramics is dependent on the pre-existing crack and flaws in the veneering material that might initiate fracture due to the high level of stresses present⁶⁰. This in return affects the strength of the bi-layer structures restorations. Other defects might be introduced during the fabrication process of the restoration during the laboratory procedures. The hand-layering technique used in making and handling the bi-layer structures is greatly operator-dependent; porosities and impurities might be introduced during the build-up, inaccurate liquid-powder proportion or even as simple as the use of a non-calibrated firing furnace. Clinically, modifications and adjustments upon delivery might also cause weakness in the material leading to premature failure of the restorations. In this study, the hand-layering technique used might have caused such weakness in the veneering material and led to chipping during TCML and the generally low fracture load values for the rest of the tested crowns.

As for the aging of the crowns in this study, it was evident that it has an influence on the restorations by reducing their fracture load in the mono-layer zirconia crowns. To date, literature provides no agreement as to what prompt aging (LTD). It is suggested that water interacts with yttrium and generates yttrium hydroxide, which eventually leads to yttrium deficiency triggering the transformation from the stable tetragonal phase to the less stable and weaker monoclinic phase⁶¹. It was also suggested that the susceptibility of yttria tetragonal stabilized zirconia to low thermal degradation is affected by low thermal treatment (200-400°C) under water vapour pressure, and different strength degradation rate occurs in the different tetragonal zirconia polycrystalline ceramics⁶². Transformation of the tetragonal to monoclinic zirconia is also reported to result from

grain size⁶³; it is inhibited with a very fine grained structure. Degradation as a result of structural phase change from tetragonal to monoclinic phase enhances the formation of a macro and micro cracks; resulting in a reduction of strength, toughness and density. This phase change is reported to occur at the surface and then into the material's depth⁶².

Both structure and geometry of the mono-layer zirconia restorations play a role in limiting the amounts of defects; by removing the interface layer between the framework and the veneer which ultimately reduces the possibility of fracture^{64,65}. However, future short and long term clinical studies are needed to investigate whether variant influencing factors present in the oral cavity, such as the different masticatory load, fluctuation of temperature accompanied with variation in the PH can play a role in determining the fracture strength of mono-layer zirconia crowns and influence their behaviour in-vivo.

4.6 Conclusions

Given the limitations of the current study, the following were concluded:

- ✓ Fracture load of mono-layer zirconia crowns was higher than that of bi-layer zirconia-based crowns.
- ✓ Bi-layer structure had 50% survival rate within 2 clinically simulated years, by having large chips on the buccal side of the crown; making them displeasing aesthetically and more prone to fracture at lower mastication loads.
- ✓ Hybrid-abutment zirconia-based crown are unlikely to fracture and should have satisfactory clinical performance in withstanding molar masticatory loads.
- ✓ Short and long-term clinical trials are necessary to determine the final evaluation of materials and hybrid-abutment crowns performance in-vivo.

4.7 Acknowledgments

The authors would like to thank Ivoclar Vivadent for providing the materials required for this study. We are also grateful for Mr. Ian Underhill from Griffith University School of Engineering for his help in the mechanical fracture testing. Finally, would like to acknowledge Central Analytical Research Facility operated by the Institute for Future Environment at QUT for their help in SEM imaging.

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Linking page

Chapter four looked into the fracture resistance of monolithic and veneered zirconia-based crowns in simulated oral environment. It was concluded that the monolithic structures is more resistant to fracture compared to the veneered structure and hence, it is more capable to withstand occlusal loads in the posterior region of the oral cavity.

The next chapter will concentrate on the bi-layer structural form of the zirconia-based hybrid-abutment crowns when supported by implants. The impact of veneering technique on the post-fatigue fracture resistance will be discussed.

The chapter was also written as a journal article and submitted to the peer-reviewed journal for publication and it has the following bibliographic details:

Elshiyab S.H, Nawafleh N, Khan U, George R. Impact of Veneering Technique on The Survival of Implant-Supported Zirconia-Based Hybrid-Abutment Crowns. The paper is submitted for publication.

Chapter Five

Impact of veneering technique on the survival of implant-supported zirconia-based hybrid-abutment crowns

Original research paper
(Submitted for publication)

STATEMENT OF CONTRIBUTION TO CO-AUTHORED PUBLISHED PAPER

This chapter includes a co-authored paper. The bibliographic details (if published or accepted for publication)/status (if prepared or submitted for publication) of the co-authored paper, including all authors, are:

Elshiyab S.H, Nawafleh N, Khan U, George R. Impact of Veneering Technique on The Survival of Implant-Supported Zirconia-Based Hybrid-Abutment Crowns. The paper is submitted for publication.

My contribution to the paper involved: study protocol, experimental design and samples preparation, data collection, statistical analysis and preparation of the manuscript.

(Signed)

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5.1 Abstract

Objectives. To investigate the influence of veneering technique (hand-layering vs. milling) on the fracture resistance of bi-layer implant-supported zirconia-based hybrid-abutment crowns.

Materials and methods. Mandibular molar copings were anatomically designed and milled. Copings were then veneered by hand-layering (HL) (n=20) and milling using the Cad-On technique (LD) (n=20). Crowns were cemented to zirconia hybrid-abutments. Ten samples of each group acted as a control while the remaining ten samples were subjected to fatigue in a chewing simulator. Crowns were loaded between 50 N and 100 N for 1.2 million cycles under simultaneous temperature fluctuation between 5°C and 55°C. Crowns were then subjected to static load to fracture test. Data was statistically analysed using the One-way ANOVA. Randomly selected crowns from each group were observed under scanning electron microscopy to view fractured surfaces.

Results. During fatigue, LD crowns had 100% survival rate; while HL crowns had 50% failure rate. Fracture resistance of LD crowns was statistically significantly higher than that of HL crowns at baseline and after fatigue ($P \leq 0.05$). However, fatigue did not cause statistically significant reduction in fracture resistance in both LD and HL groups ($P > 0.05$). Copings fractured in the LD crowns only and fracture path was different in both LD and HL groups.

Conclusions. Compared to hand-layered technique, milled veneer implant-supported hybrid-abutment crowns exhibit significantly higher fracture resistance, and better withstand clinical masticatory loads in the posterior region. Also, fatigue application and artificial aging caused no significant strength reduction in both techniques.

5.2 Introduction

Being the toughest of all dental ceramics¹, zirconium dioxide has been in clinical use for over 10 years and has been found as a satisfactory coping material for tooth-supported and implant-supported restorations^{2,3}. It has reported high success rate as an abutment and as a coping material in clinical studies⁴⁻⁶. However, chipping of the veneering ceramics was the most common technical complication in its bi-layer structure; while limited coping fracture have been clinically reported^{2,5-14}. This indicates that the veneering ceramic-zirconia interface is the weakest bond. Studies investigating the bond strength between zirconia coping and the veneering ceramics reported mainly cohesive failure within the veneering ceramic^{15,16}.

Copings of bi-layer zirconia crowns can be veneered using multiple techniques such as conventional hand-layering technique, pressing technique or milling technique using the Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) technology. In conventional hand-layering technique build-up of dentin and enamel porcelain is done on the coping. However, in pressing technique the veneer is pressed on the coping using an ingot and a special press furnace; this provides superior strength¹⁷ and anatomical characteristics, yet less aesthetically favourable compared to the latter¹⁸. Moreover, veneering of the zirconia coping can be made by milling lithium disilicate structure using CAD/CAM; where the coping and the veneering structure are designed using the split-file technology and then milled separately. Later both the coping and the milled veneer structure are fused together using glass ceramic^{19,20}.

Satisfactory bonding between the coping and the veneer material is the key to bi-layered restoration success^{8,17}. Such bond strength between the veneering porcelain and the zirconia copings could result in enhanced fracture strengths. It was suggested that bond strength of the veneering porcelain to zirconia coping depends on the strength of the

porcelain itself²¹. Bond strength is also affected by differences in the coefficient of thermal expansion between the veneering material and the coping^{22,23}. Aboushelib suggested that the bond between the coping and the veneering ceramic should have a certain minimal strength to prevent chipping of the veneering ceramic under masticatory loading¹⁸.

Being more aesthetically pleasing^{24,25}, highly biocompatible and less susceptible to plaque accumulation compared to titanium structures²⁶⁻²⁸, zirconia can be used as an abutment material for implant-supported restorations in a commercially available standard form or customised form; fabricated by the dental technician using the CAD/CAM technology.

A new approach to achieve aesthetics and strength together in implant dentistry is the hybrid-abutment crown approach^{29,30}. It is considered relatively new and consists of the following components: 1) hybrid-abutment (an all-ceramic abutment and a Ti-Base), 2) all-ceramic crown. Clinically, the approach was considered to enhance aesthetics and was also regarded as reliable option in the anterior region^{29,30}. Silva et al suggests that performance of all-ceramic crowns on hybrid-abutments made with lithium disilicate abutments should be adequate clinically³¹. It is also reported that the fracture resistance of hybrid-abutment all ceramic crown is influenced by the crown's structure (monolithic vs. bi-layered)³², crown's material³² and the abutment's material, manufacturer and design³³.

To date, no information is available about the influence of the veneering technique used in the bi-layer structures on the fracture resistance of such hybrid-abutment crowns. Therefore, this study aimed to evaluate the fracture resistance and post fatigue fracture load of zirconia copings veneered with CAD/CAM milled lithium disilicate structures compared to hand-layered veneered copings when cemented to hybrid-abutments and

supported by implants. We hypothesised that implant-supported hybrid-abutment crowns veneered with milled lithium disilicate ceramic will exhibit similar survivability as well as fracture loads to failure compared to hybrid-abutment crowns veneered by hand-layered nano-fluorapatite ceramic. We also hypothesised that fatigue testing in simulated oral environment will not significantly affect fracture loads for crowns made in either techniques.

5.3 Materials and Methods

5.3.1 Sample preparation

For the purpose of this study, hybrid-abutments (Figure 5.1) were used and anatomically correct bi-layer crowns for a lower right first molar were veneered to the abutment using two different techniques; the milling technique (IPS e.max[®] CAD-On) (n=20) by joining a milled lithium disilicate veneering structure (LD) to the zirconia coping, and hand-layering technique (n=20) by building up dentin and enamel ceramic on the zirconia (HL). Materials and components used in this study are listed in table 5.1.

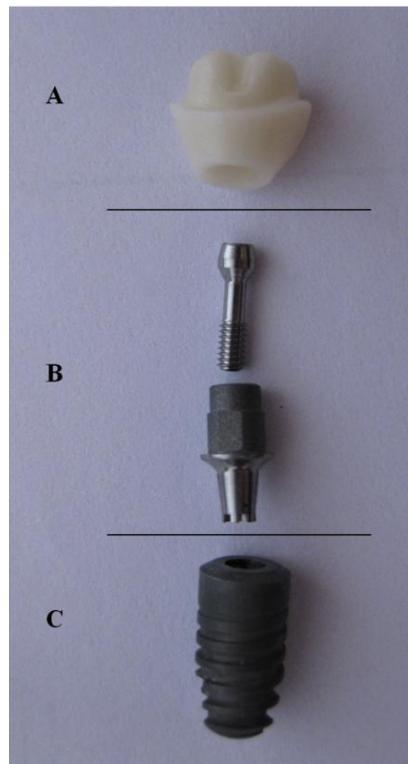


Figure 5.1. Hybrid-abutment used for this study; (A) zirconia abutment (B) Ti-Base (with screw) (C) Ankylos[®] implant (C)

Table 5.1 Study components and materials

Component	Description	Manufacturer
Forty implants	5.5 mm diameter Ankylos [®] C/X titanium implants	DENTSPLY–Friadent GmbH, Mannheim, Germany
Forty hybrid-abutments		
1. Titanium base (Ti-Base)	1. Internal Ankylos [®] compatible Ti-Base; 1.00 mm hex screw, 4 mm height and 0° angulations.	1. Dess, Dental Smart Solutions, Montcada, Spain.
2. Zirconia abutments	2. Zirconia abutments with 1.0 mm depth shoulder	2. Zenostar, Ivoclar Vivadent, Lichtenstein, Germany
Forty copings	Anatomically designed as per manufacturer recommendations of minimum thickness (0.6 mm circular and 0.7 occlusal) and milled from pre-sintered zirconia discs	Zenostar, Ivoclar Vivadent, Lichtenstein, Germany
Veneering material	1. Hand-layered nano-fluorapatite ceramic. IPS e.max Ceram (0.7 mm circular and 0.8 occlusal). 2. Milled lithium disilicate blocks, IPS e.max CAD (0.7 mm circular and 0.8 occlusal)	Ivoclar Vivadent, Lichtenstein, Germany

CAD-On crowns were designed using the split-file technique (3Shape, Copenhagen, Denmark); anatomical zirconia coping was designed first and followed by designing the lithium disilicate veneering structure (See Appendix 1). The zirconia abutments and the CAD-On design files were then transferred to a 5-axis milling machine (ZENOTEC[®] select, Wieland Dental, Lindenstraße, Germany) to mill zirconia abutments (n=40) and zirconia copings (n=40). Zirconia structures were then sintered in the recommended Programat S1[®] furnace (Ivoclar Vivadent, Schaan, Liechtenstein) and left to slow cool.

5.3.1.1 Manufacturing process for CAD-On crowns (LD)

In a wet milling machine (ZENOTEC[®] select hybrid, Wieland Dental, Lindenstraße, Germany), LD veneering structures (n=20) were milled from the same CAD-On design file previously used to mill the zirconia abutments and copings. Afterwards, fitting was checked for; a) zirconia abutments to the Ti-Base, zirconia copings to zirconia abutments and c) LD veneering structures on the zirconia copings. Afterwards, IPS e.max[®] Crystall./Connect capsule was mixed using the Ivomix (Ivoclar Vivadent, Schaan, Liechtenstein) and evenly distributed on the occlusal aspect of the zirconia copings as well as on the fitting surface of the LD veneering structures. Both copings and veneering structures were then joined together using Crystall./Connect and any excess material was removed from the circular fusion joint. To verify correct join between the coping and the veneering structure, all LD crowns were checked for occlusion in an articulator. The recommended Fusion/Crystallisation firing of the LD crowns was conducted in a Programat EP 3010[®] furnace (Ivoclar Vivadent, Schaan, Liechtenstein). Finally, LD crowns were glazed and recommended glazing firing was also conducted in the same Programat 3010[®] furnace. Firing conditions for hand-layered crowns were previously listed on page 108. Firing conditions for CAD-On crowns are listed in table 5.2.

Table 5.2 Firing conditions for CAD-On crowns

	Fusion/Crystallization firing CAD-on	Glaze firing
Stand-by temperature B (°C)	403	403
Closing time S (min)	02:00	06:00
Temperature increase t (°C/min)	30/30	60/30
Holding temperature T (°C)	830/850	830/850
Holding time H (min)	02:00/00:07	00:10/03:00
Vacuum 1 V1 (°C)	550/830	550/830
Vacuum 2 V2 (°C)	830/850	830/850
Long-term cooling L (°C)	610	610
Cool down gradient tI (°C)	off	off
Pre-drying temperature (°C)	403	off
Pre-drying time (min)	06:00	00:00

5.3.1.2 *Manufacturing process for hand-layered crowns (HL)*

Using IPS e.max[®] Ceram (Ivoclar Vivadent, Schaan, Liechtenstein), hand layering of the zirconia copings was done by a dental technician of 25 years' experience. Silicone index of an LD crown was taken and used during the porcelain build-up process of dentin and enamel porcelain of the HL crowns; to ensure standardisation of both anatomical shape and thickness of the layering porcelain in both LD and HL crowns. Then, all crowns were glazed as per the manufacturer recommendation using the IPS e.max Ceram glaze. Firing of the dentin porcelain, enamel porcelain and glazing was

conducted as per manufacturer recommendation in a Programat 3010[®] furnace (Ivoclar Vivadent, Schaan, Liechtenstein).

5.3.2 In-vitro testing

To cement the crowns to the Ti-Base, the Ti-Base access hole was first filled with a temporary restorative material (Fermit N; Ivoclar Vivadent AG, Schaan, Liechtenstein), and zirconia abutments were then luted to the Ti-Base using a self-curing dental luting composite (Multilink[®] Hybrid Abutment, Ivoclar Vivadent, Schaan, Liechtenstein) as per manufacturer instructions.

Twenty-four hours later both LD and HL crowns were adhesively luted to the zirconia abutments using Multilink[®] Automix (Ivoclar Vivadent, Schaan, Liechtenstein) as per manufacturer instructions. Specimens were stored in distilled water at 37°C for a minimum of 7 days prior to testing³⁴.

Both LD (n=20) and HL (n=20) groups were then divided into two subgroups (n=10) according to the testing to be conducted; 1) control group (non-fatigued) crowns to be subjected to static load to fracture (SLF) in a universal testing machine 2) test group (fatigued) to undergo thermal cycling mechanical loading in a chewing simulator prior to SLF test.

To prepare samples for fatigue testing (Figure 5.2) in the chewing simulator (CS-4.8; SD Mechatronik GmbH, Feldkirchen-Westerham, Germany), all implants were inserted in acrylic resin base (Palapress vario, Heraeus Kulzer Wehrheim, Germany) up to the first thread to simulate clinical procedures; the acrylic resin modulus of elasticity (12 GPa) approximates that of human bone (18 GPa)³⁵. In addition, a jig especially designed for the SLF test to fit samples of study subgroups and to ensure that samples are stable during compressive loading as well as to prevent any lateral movement of samples;

samples had no angulations and the load was applied vertically using a 6-mm diameter stainless steel spherical indenter.

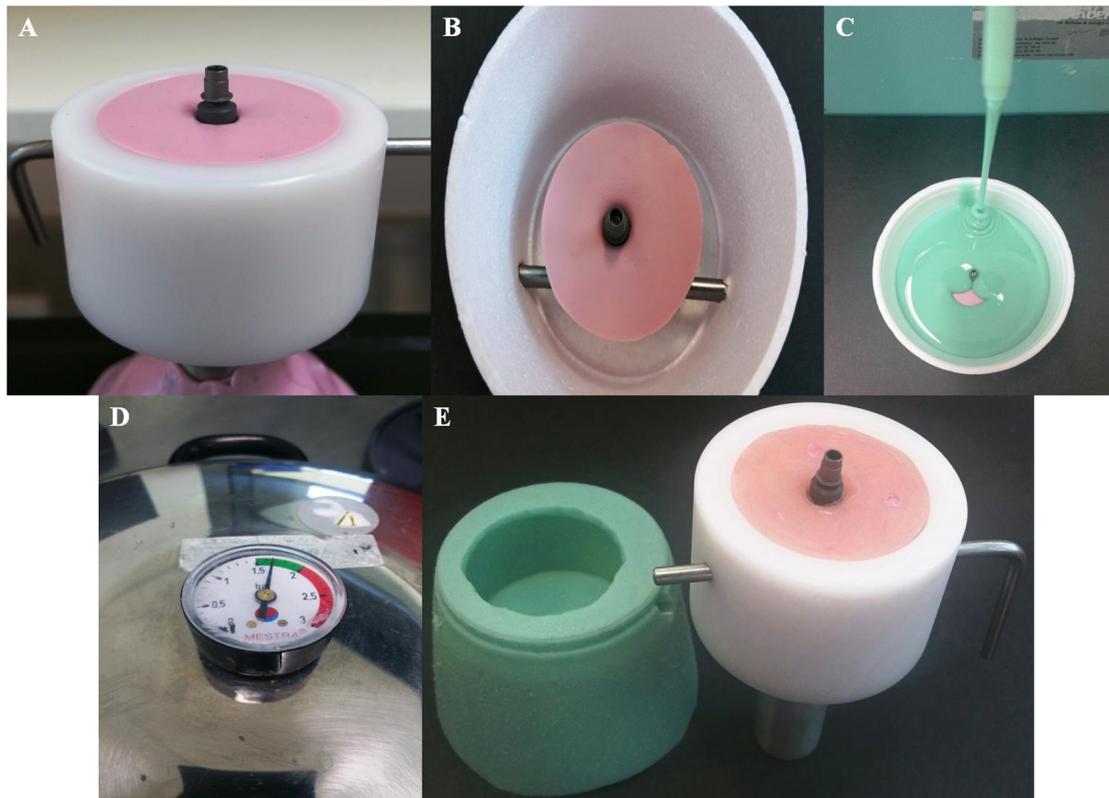


Figure 5.2. Fabrication of sample cup holder for fatigue testing; (A) Implants were screwed into heavy putty (Coltene whaledent, Altstatten/Switzerland) (B) Ti-Base abutment torqued to implant and ready to pour duplicate material (C) Silicone duplicate material (Exaktosil N21, Bredent) poured into the cup (D) silicone replica put to set in a pressure pot to avoid porosity (E) Silicone replica of sample cup with implant and Ti-Base abutment inverted and Acrylic resin (Palapress vario, Heraeus Kulzer Wehrheim, Germany) poured in the mold and checked in the original chewing simulation sample cup for fitting

5.3.3.1 Thermal cycling mechanical loading (fatigue)

Using a 6-mm diameter stainless steel spherical indenter and a loading frequency of 1.2 Hz, crowns were loaded for 1,200,000 cycles in a chewing simulator to simulate 5 years of clinical service³⁵⁻³⁷. Loading protocol was as follow: crowns initially loaded with 50 N for 250,000 cycles, the following 500,000 cycles were loaded with 100 N, and the last 450,000 cycles were loaded with 50 N. To simulate aspects of natural masticatory settings during testing³⁸, indenters were positioned with mouth opening of 6 mm to simulate natural masticatory function, and 0.5 mm lingual to the disto-buccal cusp tip

and sliding 0.3 mm lingual³⁹ to the central fossa. Throughout the testing (Figure 5.3), crowns underwent simultaneous thermal cycling between 5°C and 55°C in distilled water (5118 thermal cycles, 60 s dwell time, and 15 s pause time to empty the chambers). At the end of each loading stage, each crown was inspected under an 8x magnification using an endodontic microscopy (GLOBAL A-Series™, Global Corp., MO, USA) for the presence of any chipping, cracks or fractures. All crowns that had visual evidence of chipping or cracking were removed from further fatigue testing.



Figure 5.3. Crowns undergoing thermo-cycling in a chewing simulator during fatigue testing

5.3.3.2 *Compressive static load to fracture testing (SLF)*

Both control groups (not subjected to TCML) were subjected to compressive SLF loading test (Instron, Model 3367, Massachusetts, United States) until failure. The compressive loading was applied on the crowns at three points (the triangular ridges of both lingual cusps and the disto-buccal cusp as shown in figure 5.4) at a crosshead speed of 1 mm/min⁴⁰.



Figure 5.4. Position of the indenter during the compressive testing

5.3.3 Scanning Electron Microscopy (SEM)

After fracture resistance testing, randomly selected crowns from each group were selected and observed by using the TESCAN scanning electron microscopy (SEM) (Mira 3XMU, Kohoutovice, Czech Republic), to check the fractured surface condition and highlight any differences between the groups (if present). Sputter coating of the crown was done with gold (Leica EM SCD050, Wetzlar, Germany) to a thickness of approximately 10 μm prior to imaging.

5.3.4 Statistical analysis

Statistical analysis of the data was conducted using the SPSS software (version 24.0; IBM, Chicago, USA). Skewness and Kurtosis tests and P-P Plots were used to check the normality of data distribution. One-Way ANOVA was used to compare means and to evaluate statistical significance between all study groups. Post-Hoc assessment was performed using Tukey HSD test. T-test was also conducted to analyse data of the HL crowns of the fatigued group (survived *vs.* failed). A *p* value equal to or less than 0.05 was set to indicate statistical significance.

5.4 Results

5.4.1 Thermal cycling mechanical loading (fatigue)

No implants fracture occurred during fatigue in the chewing simulator in both LD and HL groups. Also, no failure occurred for the LD crowns during chewing simulation. Nevertheless, HL veneered crowns failed by means of chipping under the indenter contact point during chewing simulation and at different number of cycles; two crowns failed during the first stage of the loading protocol under 50 N; at the end of 250,000 cycles. Also, three crowns failed during the second stage of the loading protocol under 100 N; one failed at 418,000 cycles and the other two failed at the end of the 500,000 cycles. Wear facets on the occlusal contact of the indenter were evident in both LD and the survived HL crowns (Figure 5.5).



Figure 5.5. Wear facets at the indenter occlusal contact upon completion of chewing simulation (arrows) (A) milled lithium disilicate veneer (B) hand-layered veneer and (C) arrow indicating the chipping on the disto-buccal cusp at the indenter occlusal contact during chewing simulation

5.4.2 Static load to fracture (SLF)

The ultimate fracture load values (standard deviation) recorded in newtons for un-fatigued crowns were as follows:

Crowns veneered with milled lithium disilicate (n = 10):

F = 4625 N (507)

Hand-layered veneered crowns (n = 10):

F = 1640 N (130)

On the other hand, the ultimate fracture loads values (standard deviation) recorded in newtons fatigued crowns were as follows:

Crowns veneered with milled lithium disilicate (n = 10):

F = 3897 N (446)

Hand-layered veneered crowns (n = 10):

F = 1258 N (66)

Mean and standard deviation of fracture loads in Newtons (N) for all study groups is presented in figure 5.6. Normal distribution of data was confirmed by Skewness and Kurtosis as well as the P-P Plots. In addition, one-way ANOVA analysis showed that LD crowns had statistically significant higher fracture resistance ($p \leq 0.05$) than HL crowns. However, there was no statistically significant difference between the control and the fatigued crowns in both groups.

Upon conducting the SLF test, it was observed that crowns of HL subgroups had a cohesive fracture of the veneering on the lingual cusps which extended to the coping-ceramic interface with no fracture of the coping. On the contrary, both veneer structure and copings fractured in LD subgroups. In addition, no ceramic abutments, Ti-Base or implants were fractured and no screw loosening occurred in any of the groups.

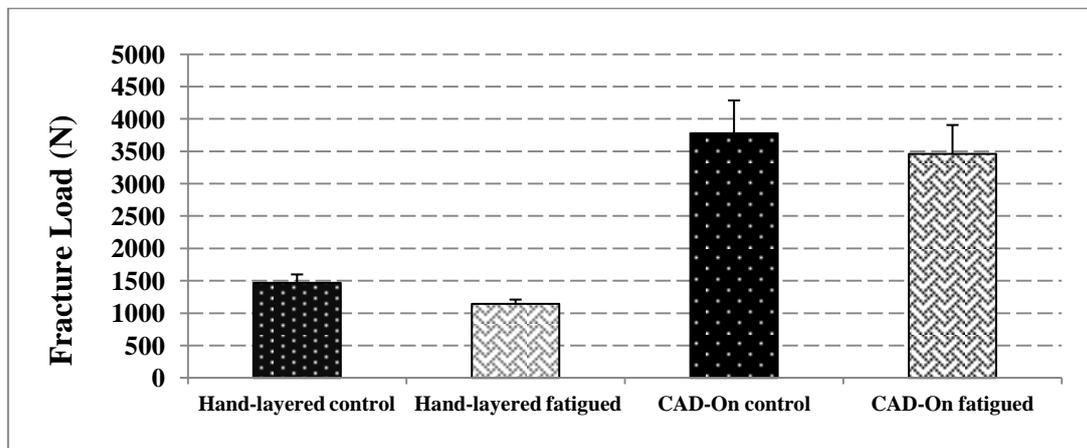


Figure 5.6. Mean and standard deviation of fracture loads in Newtons (N) for all study groups

5.4.3 Scanning Electron Microscopy (SEM)

Representative SEM images of fractured surfaces are presented in figure 5.7. Presence of pores in the veneering layer was evident. Hackles and wake hackles were also present on both LD and HL fractured surfaces, which indicates the orientation of crack.

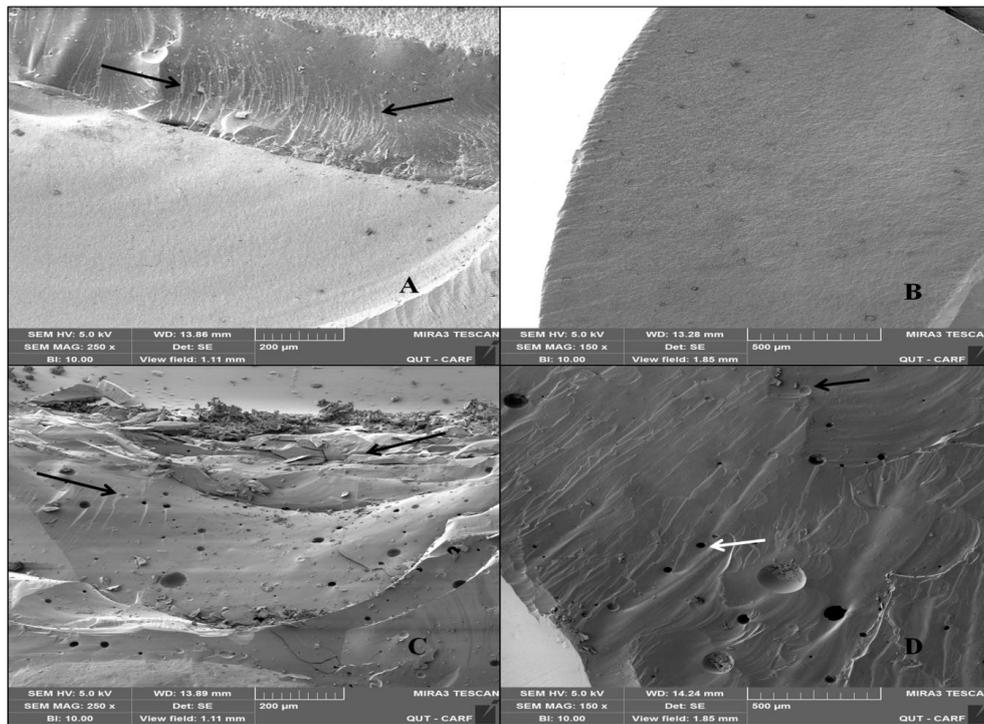


Figure 5.7. Representative SEM images of fractured surfaces for (A) milled lithium disilicate veneer at 250x showing hackle lines (arrows) and (B) buccal view of lithium disilicate veneer 150x, (C) view of the occlusal surface shows catastrophic chipping of the veneering porcelain (pointer) in the hand-layered veneer at 250x (D) a buccal view of the hand-layered veneer showing wake hackles as an distinctive indicator of crack propagation (black arrow) as well as pores (white arrow)

5.5 Discussion

This study looked at bi-layer zirconia-based implant-supported hybrid-abutment crowns in the posterior region. Our results showed that zirconia-based copings for hybrid-abutment crowns veneered with lithium disilicate veneer had significantly higher fracture load to failure compared to the hand-layered veneer. Also, fatigue did not cause significant reduction in fracture resistance for crowns veneered in either technique with milled lithium disilicate veneers resulting in 100% survival rate. Nonetheless, some hand-layered veneered crowns failed during fatigue testing by means of chipping. These findings reject our hypothesis that hybrid-abutment crowns made of zirconia copings and veneered with milled lithium disilicate exhibit similar fracture loads and survivability compared to crowns with hand-layered veneers. However, the hypothesis that fatigue testing will have no significant effect on the fracture load of hybrid-

abutment crowns veneered in both techniques was accepted. Past experimental or clinical studies provide no semblance to the current work. Thus, results of this study maybe hard to be directly compared to other studies conducted on hybrid-abutment crowns.

Fracture resistance of crowns with CAD/CAM lithium disilicate veneer was significantly higher than that of the hand-layered veneers. Studies on tooth-supported crown reported the same results with CAD/CAM veneered zirconia coping displaying significantly higher fracture loads compared to the hand-layered veneers⁴¹⁻⁴³. Fracture load values of CAD/CAM lithium disilicate veneers reported in all the previous study and in the current studies are all higher than the maximum chewing forces⁴⁴⁻⁴⁶.

Five crowns of the hand-layer veneered group suffered chipping of the veneer during fatigue testing on the cusp where the indenter was loaded. High veneer chipping in hand-layered zirconia-based restoration was also reported in a previous study which compared both veneering methods in tooth-supported crowns²⁰. Kassem et al reported that cyclic loading caused cracks in the zirconia based crowns⁴⁷. After further crowns testing Kassem et al reported micro-leakage to the dentine caused by the present cracks⁴⁷. Although the study was done on natural teeth; however, this micro-leakage might also occur in chipped or cracked implant-supported crowns which can possibly extend to the abutment and the implant leading to periodontal problems and cause peri-implantitis.

Such significant difference in fracture load values between both veneering techniques might be due to differences in both veneering materials and fabrication techniques used; while lithium disilicate veneer has a flexural strength of 360 MPa, the veneering ceramic used in the hand-layering technique has a flexural strength of 90 MPa making

the later more prone to failure at low loads during mastication⁴⁸. Also, lithium disilicate veneers were milled using the CAD/CAM technology, which is a controlled technique following certain procedure where human error is not as an significant factor⁴⁹; that allows for very minor flaws and structural defects in the veneering ceramic and result in an enhanced strength. In addition, the zirconia coping is subjected to few firing cycle, which reduces the likelihood of thermal fatigue⁵⁰. However, the conventional hand-layering technique is operator-dependant and requires a superior technical expertise to achieve aesthetics and despite following the ultimate attention to applying the layering details and firing procedures; porosity, voids and maybe micro gaps at the coping-ceramic interface is most likely to occur during layering^{50, 51} and may be responsible for veneer fracture.

In the oral cavity, chipping usually occurs after exposure to a localised load on one or more cusp during mastication while undergoing aging at the same time⁴². For the purpose of replicating real word clinical scenarios, anatomically correct crowns with coping and veneering structure of all the groups fabricated according the minimum recommended thickness used for clinical restorations. Also, identical veneering thickness and occlusal morphology was done for all tested crowns. In addition, laboratory procedures for milling the copings and veneering them in the previously mentioned techniques, as well as the cementation were done as per manufacturer recommendations. Moreover, crowns were exposed to a testing method that closely mimics the clinical scenario; which was achieved by using the chewing simulator to apply mouth-motion fatigue loads as well as applying simultaneous temperature fluctuation. The mouth-motion fatigue causes failures which start from the indenter loading point in the outer and inner cone crack forms and then extends to the veneer/core interface⁵² which closely simulates the failure behaviour of crowns in the clinical condition⁵³. Although not statistically significant, crowns, which underwent

aging by means of thermocycling, had lower mean fracture load values. The wear facets that were observed on the surface of all crowns where the indenter loading occurred may have caused inner cracks, weakening the veneering material and reducing the fracture resistance; this observation was also reported by Schmitter et al (2012)⁴².

Neither implants nor any of the hybrid-abutment components fractured/failed in this study. Loads applied to the implant-supported crown can be transmitted to other parts of the crown system, which would increase the stresses on both the ceramic abutment and abutment–implant junction. The current study findings suggest that adhesive bonding of the zirconia abutment to the Ti-Base which can withstand occlusal forces and therefore, would be considered a favourable clinical approach.

5.6 Conclusions

Within the limitation of the current study, the following were concluded:

- ✓ Veneering hybrid-abutment zirconia-based crowns using milled lithium disilicate structure creates a crown with high fracture resistance properties, and may result in highly clinically reliable restorations.
- ✓ Crowns veneered using the conventional hand-layering technique are likely to fail by chipping of the veneering layer early during clinical service; which makes them unfavourable and less cost effective for both clinician and patient.
- ✓ The combination of zirconia abutment to a Ti-Base (hybrid-abutment) has an adhesive bond which is unlikely to fail during clinical service.
- ✓ Short and long-term clinical trials are necessary to assess implant-supported hybrid-abutment crowns veneered in both veneering techniques.

5.7 Acknowledgments

The authors would like to thank Ivoclar Vivadent for supplying the materials required for this study. We are also thankful for Mr. Ian Underhill and Mr. Chuen Yiu Lo from

Griffith University School of Engineering for their assistance in the Instron machine testing. Finally, would like to acknowledge Central Analytical Research Facility operated by the Institute for Future Environment at QUT for their help in SEM imaging.

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Linking page

The previous chapters looked at implant-supported hybrid-abutment crowns fabricated from all-ceramic materials; zirconia-based and lithium disilicate crowns. Focused research was conducted on the zirconia-based hybrid-abutment crowns using different structural forms; monolithic and bi-layer. Bi-layer crown structures were further examined to highlight differences between two veneering techniques; milling and hand-layering.

The following chapter involves a general and comprehensive discussion of all the previously discussed results. It will also include clinical implication, limitations of all the included studies as well as recommend future research.

Chapter Six

**General discussion and conclusion, clinical implication,
limitations and future recommendations**

6.1 General discussion and conclusion

This doctoral thesis evaluated fatigue and fracture resistance of the newly introduced approach to implant-supported restorations; the hybrid-abutment crowns. It focused on one of the current and most appealing all-ceramic restorative material; the zirconia-based ceramics. A thorough systematic review was initially done to identify limitations in existing literature prior to design of the current in-vitro study of the implant-supported zirconia-based crowns. The systematic review explored the in-vitro survival rate of zirconia-based crowns in an aqueous environment to the in-vivo survival rate. Further, different laboratory testing conditions used in-vitro were assessed and discussed. The review provided an understanding of the most clinically relevant in-vitro settings to apply when testing restorative materials.

To ensure clinically relevant conditions, the set experimental design applied in this research involved mechanical testing by means of chewing simulation and thermal cycling. For the purpose of the included research studies; implant-supported zirconia-based hybrid-abutment crowns were fabricated in different structures, and different materials were used to achieve the aims that have been discussed in chapters 3, 4 and 5.

Based on the comprehensive systematic review of the literature presented in chapter 2, the survival rates results of in-vitro studies conducted under thermal cycling were closer to the clinical survival rates reported in the literature¹. Also, Crown's structure (monolithic vs. bi-layer) plays a role in influencing the restoration survival rate. Moreover, multiple parameters (i.e. indenter material and geography, antagonist, aging, lateral movement, frequency, force magnitude), are used while evaluating crown's behaviour in the in-vitro testing²⁻⁵. Utilising any of the previously mentioned parameters

will influence the zirconia-based crown's behaviour and results will vary across the studies. Thus, making it hard for researchers to compare obtained data to literature and to adopt a standardised in-vitro study design that would be most clinically relevant. The results of the systematic review concluded that international standardisation be set to regulate the parameters used in the in-vitro tests. In-vitro studies on implant-supported zirconia-based crowns were limited (three studies); with no reports available on hybrid-abutment crowns.

Accordingly, testing of implant-supported hybrid-abutment crowns fabricated in different structures and utilising different materials and fabrication techniques was essential. The experimental design used in the presented studies was set based on the literature of what would be more clinically relevant, and it was standardised across to allow for comparability of data obtained from all the conducted studies. The lack of literature on implant-supported hybrid-abutment crowns makes it hard to compare with previous literature. It is however important to acknowledge that the current work provides substantial information to cover this void in literature

Due to the various mastication loads which exist in the oral cavity⁶, all attempts were made to achieve a clinically relevant testing model^{7,8}. Study samples were exposed to mechanical loading by means of chewing simulation of 1.2 million cycles to simulate 5 clinical years of service⁹ and loads of 50 N and 100 N were used^{10,11} during fatigue testing. A frequency of 1.2 Hz was used to replicate mean in-vivo frequency¹². Furthermore, samples underwent thermal cycling with temperature fluctuation; to mimic the influence of aging on dental ceramics.

Chapter 3 showed that Hybrid-abutment monolithic crowns made from lithium disilicate ceramic had significantly lower fracture resistance compared to zirconia-based hybrid-abutment monolithic crowns after simulation of 5 clinical years. This may be

due to the crystalline structure that zirconia-based ceramic possess, which is considered of a high strength¹³. However, although strong, aging of the crowns during fatigue testing significantly reduced both materials fracture resistance. Strength degradation might occur during clinical service due to the changes in the pH, exposure to water and temperature, which could influence the all-ceramic material^{14,15} and accelerate the low thermal degradation mechanism and cause reduction to fracture resistance.

As zirconia-based ceramics are opaque, zirconia-based copings are layered with a veneering ceramic to offer the restoration with the necessary aesthetics¹⁶. Chapter 4 reported that post fatigue fracture resistance of monolithic (mono-layer) structure zirconia-based hybrid-abutment crowns was statistically significantly higher than the bi-layer structure. In addition, bi-layer structures chipped by 50% during fatigue while none of the monolayer structure samples failed. The significantly higher fracture resistance is maybe a result of using the CAD/CAM technology which uses homogenous blanks and has the capacity to produce structure of minimal flaws and micro-structural; which makes them perform well when used in the molar region and supported by implants¹⁷. In addition, bi-layer structures veneered through hand-layering technique are operator-dependant and inducing structural defects such as air bubbles and voids remains inevitable^{16,18}. Such defects act as stress concentration area making it highly susceptible for crack initiation and propagation and leading to chipping¹⁹. Further, fatigue and aging caused reduction in fracture resistance of mono-layer structures only.

Chapter 5 showed that variations in the veneering technique and the veneering material in the fabrication of implant-supported zirconia-based hybrid-abutment bi-layer crowns have a noticeable influence on fracture resistance values. CAD-On hybrid-abutment bi-layer crowns veneered with milled lithium disilicate had significantly higher fracture

resistance compared to conventionally hand-layered structures. Using the same material in tooth-supported crowns had the same results²⁰⁻²². Comparing both techniques, the layering technique is more sensitive and is subject to inconsistency due to the individual building (such as ceramic powder to liquid ratio and the mixing techniques) and firing procedures; which effect the percentage of structural defects and the strength of the fired veneer¹⁸. Also, the milled lithium disilicate veneer has a flexural strength of 360 MPa compared to 90 MPa flexural strength of the veneering ceramic used in the hand-layering technique; making the later more prone to failure at low loads during mastication. Moreover, the zirconia coping-veneer bond strength plays a major role^{2,23}; strength of the porcelain itself²⁴ as well as any differences in the coefficient of thermal expansion between the veneering material and the coping could be a factor that affects the bond strength^{25,26}. To prevent chipping of the veneering ceramic under masticatory loading, the bond between the coping and the veneering ceramic should have a certain minimal strength²⁷. With regards to influence of fatigue and aging, general reduction of load to fracture values was recorded for both veneering techniques; however not statistically significant.

Stresses applied on implant-supported crowns are transmitted through to the ceramic abutment and the abutment-implant junction. Throughout the fatigue testing and upon completion of the compressive load testing in all the conducted studies, all hybrid-abutment components stayed intact and implants had no fractures. This is an indication of the strong adhesive bonding between the zirconia abutments to the Ti-Base resulting in an abutment system which can withstand occlusal mastication forces and could be a favourable clinical approach.

6.2 Clinical implication

The current study provides practitioners with significant factors to choosing the acceptable combination of crown designs and prosthetic materials; which will provide patients with the appropriate treatment when replacing a missing tooth. This study suggests that practitioners are to consider monolithic crowns or milled bi-layered veneered crowns for posterior implant-supported hybrid-abutment restorations. This study also suggests that bi-layer veneered crowns are prone to early chipping during clinical service, and may not provide any further serviceable life and hence clinicians may have to recommend these crowns to be replaced. Moreover, chipped veneer might lead to further internal crack which are not clinically visible, however, they might create areas of micro-leakage and act as a favourable environment for bacterial harbour and later cause inflammation of the surrounding gum and bone.

6.3 Limitations

The use of spherical stainless steel indenter instead of natural teeth for the fatigue testing of the materials might be considered a limitation. However, standardising the various morphology of the natural teeth require a precise machining²⁸; therefore, replacing it with a sphere antagonist in the in-vitro fatigue testing has been regarded as a good and adequate approach to understand the clinical flaw mechanism²⁹.

In addition, the use of one type of hybrid-abutment system in the testing might be considered a limitation. Nevertheless, results of this study could encourage researchers to further investigate and compare other types of hybrid-abutment using specific manufacturer's brand or other generic brand and assess which could be more clinically relevant and in favour of the patients.

Since applying cyclic loading on restorative materials till failure in the laboratory simulations is considered a more reliable to analysing fatigue failure; samples

undergoing 1,200,000 cyclic loading only rather than until failure occurs might also be considered a limitation. However, cyclic loading till failure requires considerable amount of time. Hence, the regular in-vitro study approach of applying 1,200,000 cycles which was previously used in the literature was applied in this research.

6.4 Future recommended research

The hybrid-abutment-approach is a relevant new approach in the implant-supported restorations. It provides aesthetics and strength together. Results of the included studies have no resemblance in the literature, hence it is important to carry out long and short term clinical trials using the same hybrid-abutment approach to verify results and define limits of their clinical serviceability.

Since metal-ceramic is considered the gold standard in prosthodontics, it is of an importance to study and compare results of metal-ceramic to all-ceramic hybrid-abutment crowns to highlight differences and suggest any improvements on the design or material if any is present.

Although scanning electron microscopy has been used to identify characteristics of the fractured surfaced; however, Micro-CT scanning of the zirconia-based crowns during the different stages of testing is suggested to be utilised to better understand fracture mechanism. It should give a better insight to crack initiation and propagation by locating internal structural defects. It is also recommended to use the same technology to detect if any micro leakage is present as an outcome of chipping or cracking.

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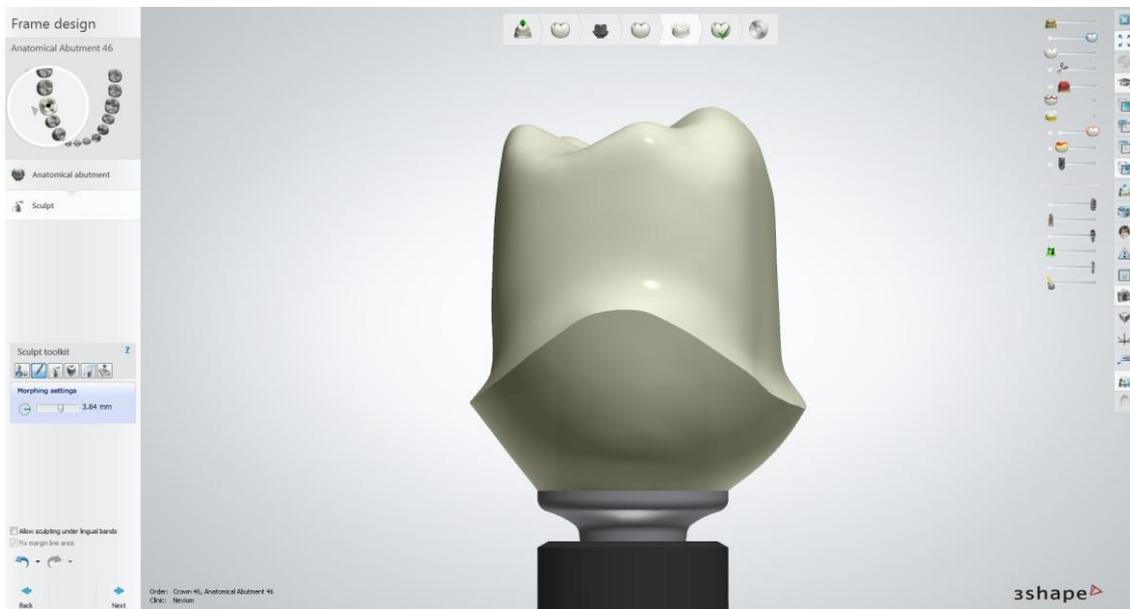
Appendix One

CAD file images of Study designs

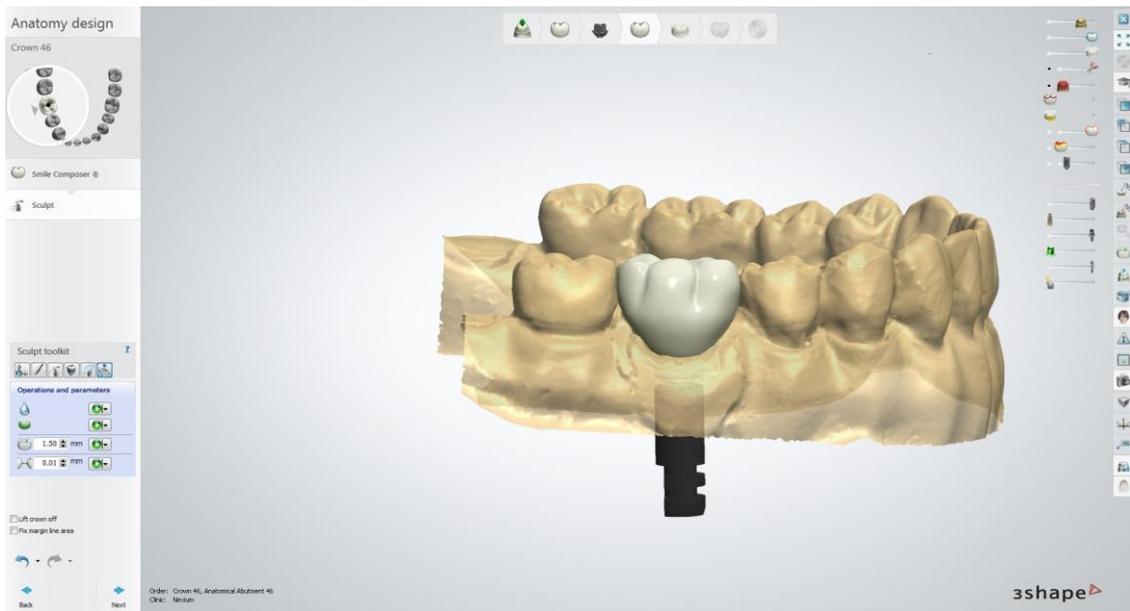
Appendix One

1. CAD file images for monolithic all-ceramic crown

1.1 Customised abutment design

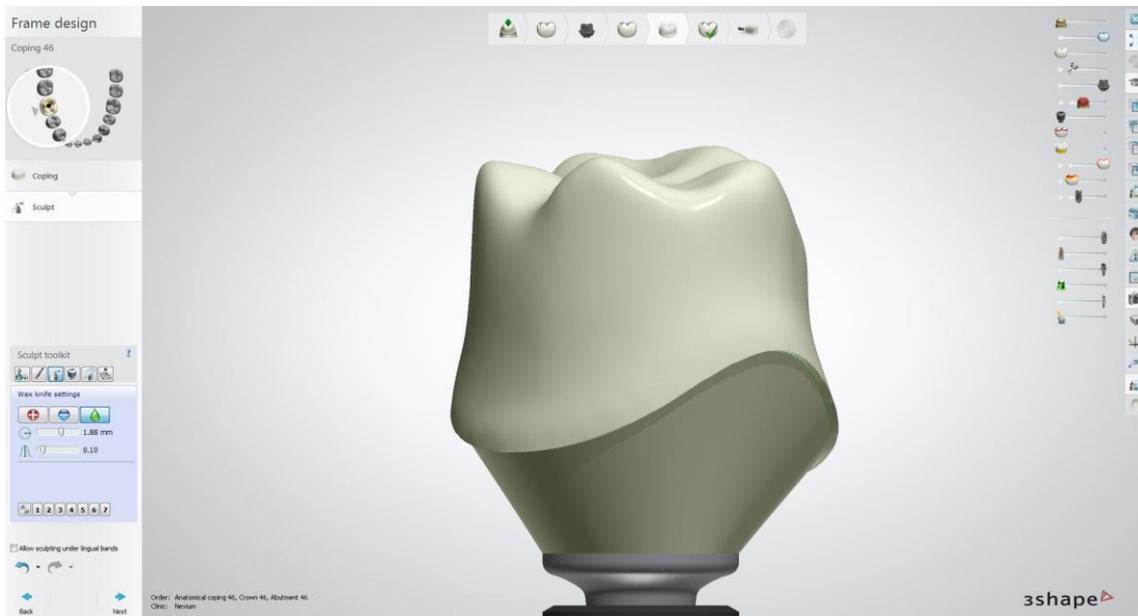


1.2 Monolithic crown design

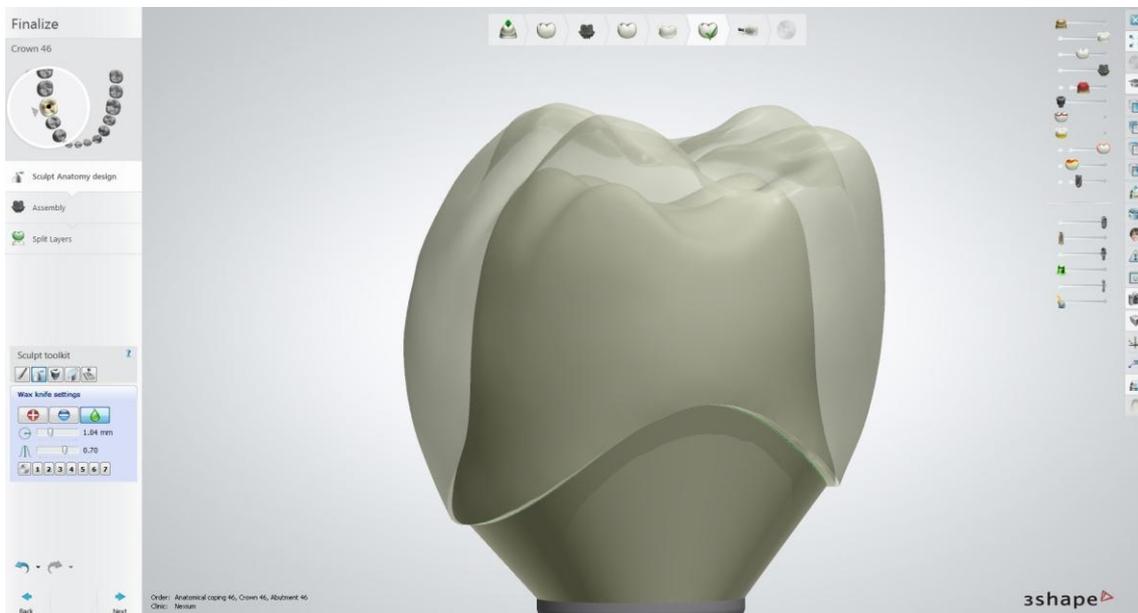


2. CAD file images for bi-layer all-ceramic crown (CAD-On and hand-layer)

2.1 Anatomical framework design



2.2 The anatomical framework and the anatomically correct veneer



2.3 The anatomically correct designed crown



Appendix Two

Fracture test statistical analysis

Appendix Two

1. Statistical analysis for monolithic zirconia crowns vs. monolithic lithium disilicate crowns

Descriptive Statistics

	N	Minimum	Maximum	Mean		Std. Deviation
	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic
Fracture Load (N)	40	1245.70	4795.70	2696.15	158.55	1002.76

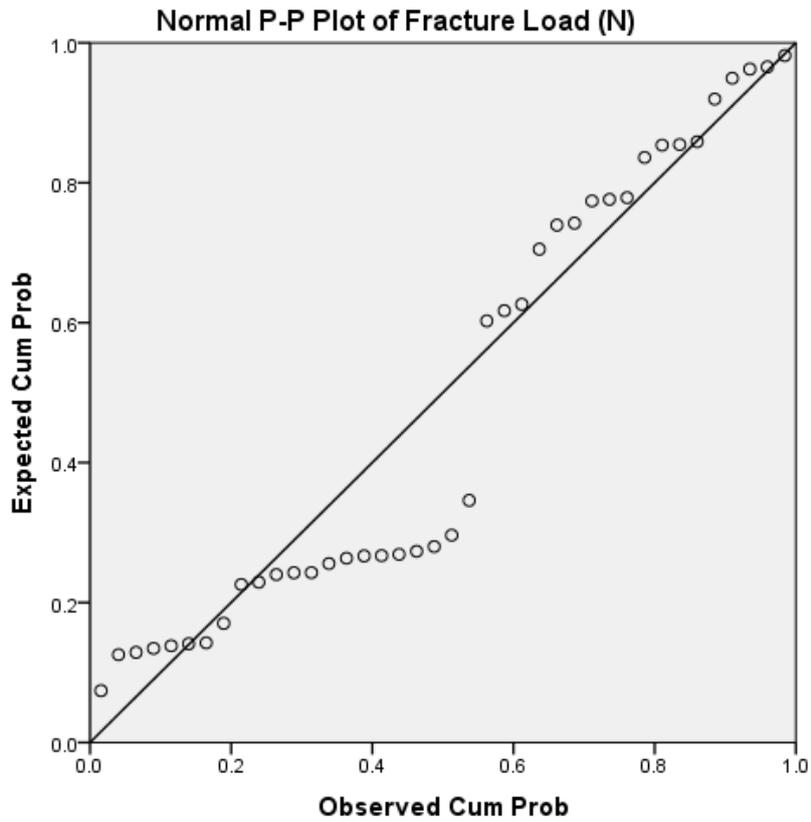
	Skewness		Kurtosis	
	Statistic	Std. Error	Statistic	Std. Error
Fracture Load (N)	.51	.38	-1.04	.74

PPlot

Model Description

Series or Sequence	1	Fracture Load (N)
Length of Seasonal Period		No periodicity
Standardisation		Not applied
Distribution	Type	Normal
	Location	estimated
	Scale	estimated
Rank Assigned to Ties		Mean rank of tied values

Fracture Load (N)



Fracture Load (N)

	Descriptive				95% Confidence Interval for Mean
	N	Mean	Std. Deviation	Std. Error	Lower Bound
SLF Mono Zirconia	10	3929.45	491.44	155.41	3577.90
CS Mono Zirconia	10	3131.47	714.30	225.88	2620.49
SLF Mono Lithium Disilicate	10	2077.43	99.58	31.49	2006.20
CS Mono Lithium Disilicate	10	1646.24	211.72	66.95	1494.79
Total	40	2696.15	1002.75	158.55	2375.45

Descriptive

Fracture Load (N)

	95% Confidence Interval for Mean		Minimum	Maximum
	Upper Bound			
SLF Mono Zirconia	4281.00		3348.20	4795.70
CS Mono Zirconia	3642.45		2071.3	4480.70
SLF Mono Lithium Disilicate	2148.66		1952.20	2298.70
CS Mono Lithium Disilicate	1797.69		1245.70	1997.00
Total	3016.84		1245.70	4795.70

ANOVA

Fracture Load (N)

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	31956578.390	3	10652192.80	52.834	.000
Within Groups	7258235.131	36	201617.64		
Total	39214813.520	39			

Multiple Comparisons

Post Hoc Tests- Fisher's least significant difference (LSD)

Dependent Variable: Fracture Load (N)

(I) Material and testing	(J) Material and testing	Mean Difference (I-J)	Std. Error	Sig.
SLF Mono Zirconia	CS Mono Zirconia	797.98 [*]	200.81	.000
	SLF Mono Lithium Disilicate	1852.02 [*]	200.81	.000
	CS Mono Lithium Disilicate	2283.21 [*]	200.81	.000
CS Mono Zirconia	SLF Mono Zirconia	-797.98 [*]	200.81	.000
	SLF Mono Lithium Disilicate	1054.04 [*]	200.81	.000
	CS Mono Lithium Disilicate	1485.23 [*]	200.81	.000
SLF Mono Lithium Disilicate	SLF Mono Zirconia	-1852.02 [*]	200.81	.000
	CS Mono Zirconia	-1054.04 [*]	200.81	.000
	CS Mono Lithium Disilicate	431.19 [*]	200.81	.039
CS Mono Lithium Disilicate	SLF Mono Zirconia	-2283.21 [*]	200.81	.000
	CS Mono Zirconia	-1485.23 [*]	200.81	.000
	SLF Mono Lithium Disilicate	-431.19 [*]	200.81	.039

Multiple Comparisons

Post Hoc Tests- Fisher's least significant difference (LSD)

Dependent Variable: Fracture Load (N)

(I) Material and testing	(J) Material and testing	95% Confidence Interval	
		Lower Bound	Upper Bound
SLF Mono Zirconia	CS Mono Zirconia	390.72	1205.24
	SLF Mono Lithium Disilicate	1444.76	2259.28
	CS Mono Lithium Disilicate	1875.95	2690.47
CS Mono Zirconia	SLF Mono Zirconia	-1205.24	-390.72
	SLF Mono Lithium Disilicate	646.79	1461.30
	CS Mono Lithium Disilicate	1077.97	1892.49
SLF Mono Lithium Disilicate	SLF Mono Zirconia	-2259.28	-1444.76
	CS Mono Zirconia	-1461.30	-646.78
	CS Mono Lithium Disilicate	23.93	838.45
CS Mono Lithium Disilicate	SLF Mono Zirconia	-2690.47	-1875.95
	CS Mono Zirconia	-1892.49	-1077.97
	SLF Mono Lithium Disilicate	-838.45	-23.93

*. The mean difference is significant at the 0.05 level.

2. Statistical analysis for implant-supported mono-layer zirconia-based hybrid-abutment crowns vs. implant-supported bi-layer zirconia-based hybrid-abutment crowns

Descriptive Statistics

	N	Minimum	Maximum	Mean		Std. Deviation
	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic
Fracture Load (N)	35	1096	4796	2600.60	206.66	1222.59

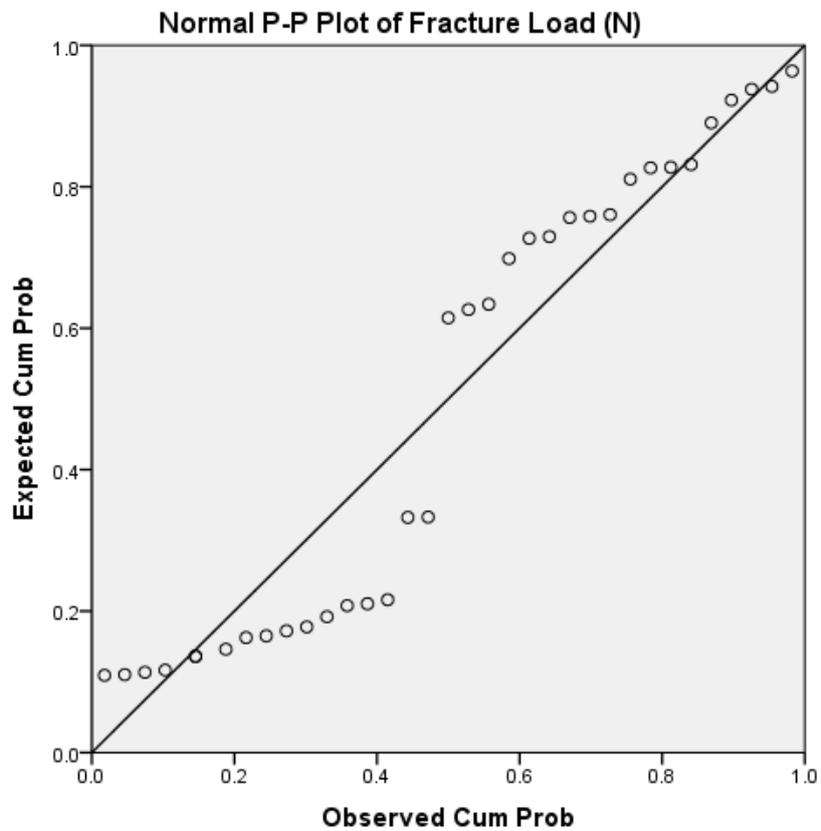
	Variance	Skewness		Kurtosis	
	Statistic	Statistic	Std. Error	Statistic	Std. Error
Fracture Load (N)	1494713.75	.191	.40	-1.51	.78

PPlot

Model Description

Series or Sequence	1	Fracture Load (N)
Length of Seasonal Period		No periodicity
Standardisation		Not applied
Distribution	Type	Normal
	Location	estimated
	Scale	estimated
Rank Assigned to Ties		Mean rank of tied values

Fracture Load (N)



Descriptive

Fracture Load (N)

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
MLZ non-aged	10	3929.45	491.44	155.41	3577.90	4281.00
MLaged	10	3131.47	714.30	225.88	2620.49	3642.45
BLZ non-aged	10	1468.94	130.12	41.15	1375.86	1562.03
BLZ aged	5	1144.47	66.10	29.56	1062.39	1226.55
Total	35	2600.60	1222.59	206.66	2180.63	3020.57

Descriptive

Fracture Load (N)

	Minimum	Maximum
MLZ non-aged	3348	4796
MLZ aged	2071	4481
BLZ non-aged	1258	1640
BLZ aged	1096	1258
Total	1096	4796

ANOVA

Fracture Load (N)

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	43884808.19	3	14628269.40	65.39	.000
Within Groups	6935459.23	31	223724.49		
Total	50820267.42	34			

Multiple Comparisons

Post Hoc Tests- honest significant difference (Tukey HSD)

Dependent Variable: Fracture Load (N)

	(I) Material and testing	(J) Material and testing	Mean Difference (I-J)	Std. Error	Sig.
Tukey HSD	MLZ non-aged	MLZ aged	797.98 [*]	211.53	.004
		BLZ non-aged	2460.51 [*]	211.53	.000
		BLZ aged	2784.99 [*]	259.07	.000
	MLZ aged	MLZ non-aged	-797.98 [*]	211.53	.004
		BLZ non-aged	1662.53 [*]	211.53	.000
		BLZ aged	1987.00 [*]	259.07	.000
	BLZ non-aged	MLZ non-aged	-2460.51 [*]	211.53	.000
		MLZ aged	-1662.52 [*]	211.53	.000
		BLZ aged	324.48	259.07	.599
	BLZ aged	ML non-aged	-2784.98 [*]	259.07	.000
		MLZ aged	-1987.00 [*]	259.07	.000
		BLZ non-aged	-324.48	259.07	.599

Multiple Comparisons

Post Hoc Tests- honest significant difference (Tukey HSD)

Dependent Variable: Fracture Load (N)

	(I) Material and testing	(J) Material and testing	95% Confidence Interval	
			Lower Bound	Upper Bound
Tukey HSD	MLZ non-aged	MLZ aged	223.87	1372.09
		BLZ non-aged	1886.40	3034.62
		BLZ aged	2081.85	3488.12
	MLZ aged	MLZ non-aged	-1372.09	-223.87
		BLZ non-aged	1088.42	2236.64
		BLZ aged	1283.87	2690.14
	BLZ non-aged	MLZ non-aged	-3034.62	-1886.40
		MLZ aged	-2236.64	-1088.42
		BLZ aged	-378.66	1027.61
	BLZ aged	MLZ non-aged	-3488.12	-2081.85
		MLZ aged	-2690.14	-1283.87
		BLZ non-aged	-1027.61	378.66

*. The mean difference is significant at the 0.05 level.

3. Statistical analysis for hand-layered zirconia-based crowns failed (chipped) vs. survived during thermal cycling mechanical testing

Descriptive Statistics

	N	Minimum	Maximum	Mean		Std. Deviation
	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic
Fracture Load (N)	10	511	1258	920.01	80.98	256.07

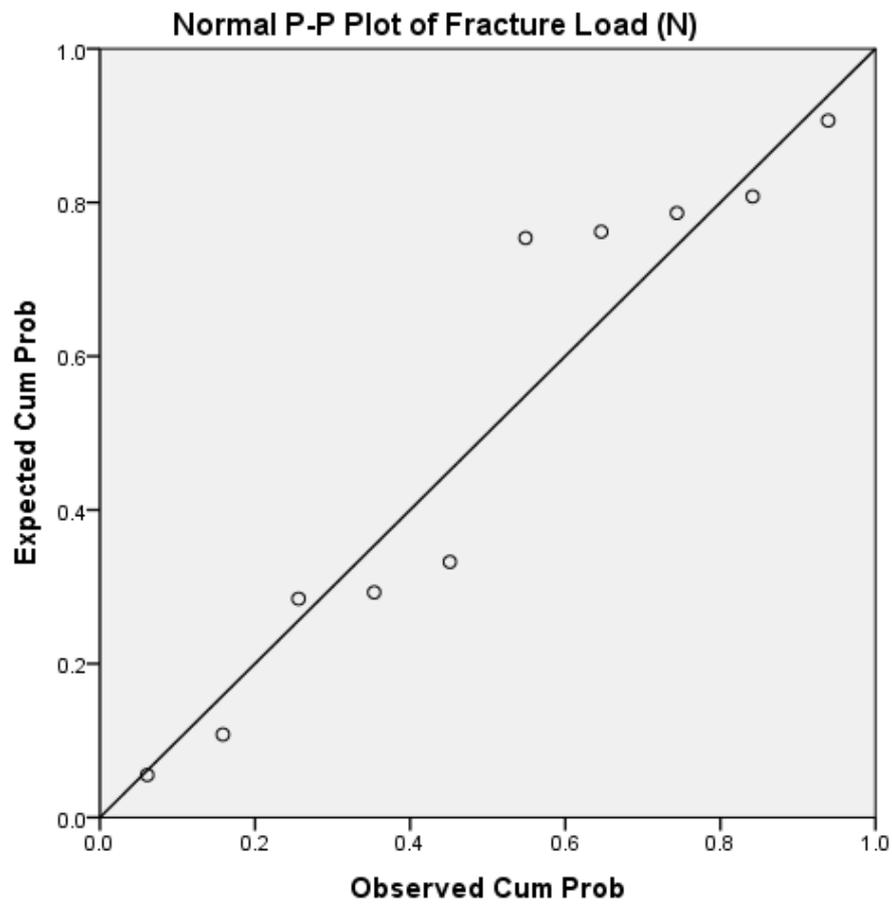
	Variance	Skewness		Kurtosis	
	Statistic	Statistic	Std. Error	Statistic	Std. Error
Fracture Load (N)	65570.94	-.31	.69	-1.38	1.33

PPlot

Model Description

Series or Sequence	1	Fracture Load (N)
Length of Seasonal Period		No periodicity
Standardisation		Not applied
Distribution	Type	Normal
	Location	estimated
	Scale	estimated
Rank Assigned to Ties		Mean rank of tied values

Fracture Load (N)



Group Statistics

	Material condition	N	Mean	Std. Deviation	Std. Error Mean
Fracture Load (N)	HL TCML survived	5	1144.47	66.10	29.56
	HL TCML Failed	5	695.56	131.21	58.68

Independent Samples Test

t-test for Equality of Means

		Sig. (2-tailed)	Mean Difference	Std. Error Difference
Fracture Load (N)	Equal variances assumed	.000	448.91	65.71
	Equal variances not assumed	.001	448.91	65.71

Independent Samples Test

t-test for Equality of Means

95% Confidence Interval of the Difference

		Lower	Upper
Fracture Load (N)	Equal variances assumed	297.39	600.43
	Equal variances not assumed	287.52	610.30

4. Statistical analysis for bi-layer zirconia-based crowns CAD-On vs. Hand-layered

Descriptive Statistics

	N	Minimum	Maximum	Mean		Std. Deviation
	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic
Fracture Load (N)	35	1096	4625	2652.06	202.74	1199.40

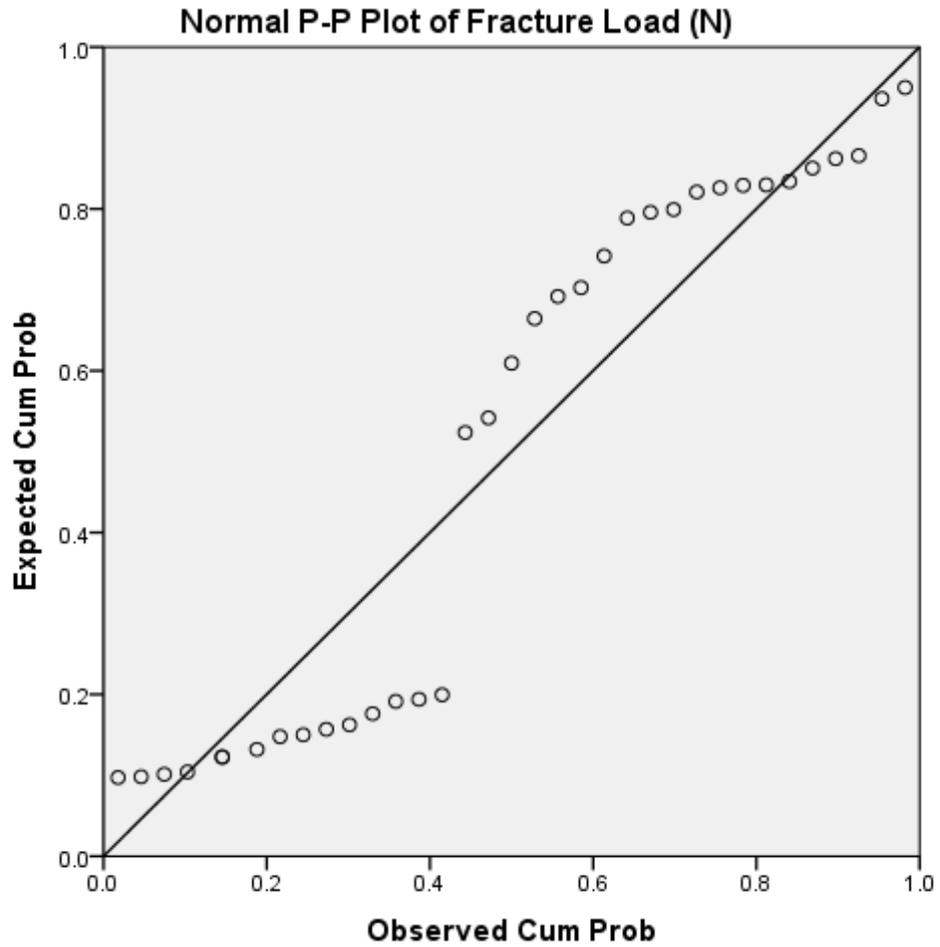
	Variance	Skewness		Kurtosis	
	Statistic	Statistic	Std. Error	Statistic	Std. Error
Fracture Load (N)	1438565.946	-.049	.398	-1.697	.778

PPlot

Model Description

Series or Sequence	1	Fracture Load (N)
Length of Seasonal Period		No periodicity
Standardisation		Not applied
Distribution	Type	Normal
	Location	estimated
	Scale	estimated
Rank Assigned to Ties		Mean rank of tied values

Fracture Load (N)



ANOVA

Fracture Load (N)

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	44629384.61	3	14876461.54	107.70	.000
Within Groups	4281857.56	31	138124.44		
Total	48911242.17	34			

Multiple Comparisons

Post Hoc Tests- honest significant difference (Tukey HSD)

Dependent Variable: Fracture Load (N)

	(I) Material and Testing	(J) Material and Testing	Mean Difference (I-J)	Std. Error	Sig.
Tukey HSD	HL Control	HL Fatigued	324.47	203.56	.397
		LD Control	-2311.11 [*]	166.21	.000
		LD Fatigued	-1992.07 [*]	166.21	.000
	HL Fatigued	HL Control	-324.47	203.56	.397
		LD Control	-2635.58 [*]	203.56	.000
		LD Fatigued	-2316.54 [*]	203.56	.000
	LD Control	HL Control	2311.11 [*]	166.21	.000
		HL Fatigued	2635.58 [*]	203.56	.000
		LD Fatigued	319.04	166.21	.241
	LD Fatigued	HL Control	1992.07 [*]	166.21	.000
		HL Fatigued	2316.54 [*]	203.56	.000
		LD Control	-319.04	166.21	.241

Multiple Comparisons

Post Hoc Tests- honest significant difference (Tukey HSD)

Dependent Variable: Fracture Load (N)

			95% Confidence Interval	
	(I) Material and Testing	(J) Material and Testing	Lower Bound	Upper Bound
Tukey HSD	HL Control	HL Fatigued	-228.01	876.96
		LD Control	-2762.20	-1860.01
		LD Fatigued	-2443.17	-1540.97
	HL Fatigued	HL Control	-876.96	228.01
		LD Control	-3188.06	-2083.10
		LD Fatigued	-2869.02	-1764.06
	LD Control	HL Control	1860.01	2762.20
		HL Fatigued	2083.10	3188.06
		LD Fatigued	-132.06	770.14
	LD Fatigued	HL Control	1540.97	2443.17
		HL Fatigued	1764.06	2869.02
		LD Control	-770.14	132.06

*. The mean difference is significant at the 0.05 level.