IN VIVO AND IN VITRO EVALUATION OF RESIN-BONDED PORCELAIN RESTORATIONS

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DECLARATION

This work contains no material which has been accepted for the award of any other degree in any university or other tertiary institution, and to the best of author's knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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TABLE OF CONTENTS

SUMMARY 1

CHAPTER ONE INTRODUCTION

1.1 INTRODUCTION **4**

1.2 HISTORY OF RESTORATIVE MATERIALS **5**

1.2.1 AMALGAM 5
1.2.2 GOLD 6
1.2.3 RESIN COMPOSITE 6
1.2.4 DENTAL PORCELAIN 7

CHAPTER TWO LITERATURE REVIEW

2.1 LITERATURE REVIEW **13**

2.1.1 MARGINAL ADAPTATION 13
2.1.2 BOND STRENGTH 17
2.1.3 PREPARATION DESIGN 24
2.1.4 PORCELAIN STRENGTH 28
2.1.5 BIOCOMPATIBILITY 39
2.1.6 CLINICAL BEHAVIOUR 41

CHAPTER THREE RESEARCH OBJECTIVES

3.1 RESEARCH OBJECTIVES **53**

CHAPTER FOUR METHODS AND MATERIALS

4.1 INTRODUCTION **55**

4.2 DEFINITION OF RESTORATIONS **55**

4.3 SAMPLE SELECTION **57**

4.4 PART ONE: RESTORATION DESIGNS AND DIMENSIONS **57**

4.4.1 PATIENT DETAILS 58
4.4.2 RESTORATION DETAILS 58

4.4.3 MEASUREMENTS....58
4.4.3.1 Intercuspal Width 59
4.4.3.2 Isthmus Width....59
4.4.3.3 Proximal Width....59
4.4.3.4 Height of axial wall 59
4.4.3.5 Depth of Occlusal Floor from the Central Fissure 60
4.4.3.6 Cusp Reduction....60
4.4.4 PREPARATION CHARACTERISTICS: 60

4.5 PART TWO: RESTORATION FAILURES AND SURVIVALS....63

4.5.1 BASELINE DATA....63
4.5.2 GENERAL ORAL FEATURES 63
4.5.3 RESTORATION INFORMATION 64
4.5.4 BASIC PROBLEMS WITH THE PREPARED TOOTH 65
4.5.5 REASONS FOR RESTORATION PLACEMENT 65
4.5.6 RECORDED DATES AND RESTORATION IDENTIFICATION 66
4.5.7 FAILURE DATA: 67

CHAPTER FIVE RESULTS AND DISCUSSIONS

INTRODUCTION 69

5.1 SECTON ONE - PREPARATION DIMENSIONS AND DESIGN....69

5.1.1 GENERAL DATA 69
5.1.2 MEASUREMENTS....71
5.1.2.1 Intercuspal Width 71
5.1.2.2 Isthmus Width....72
5.1.2.3 Proximal Width....73
5.1.2.4 Height of Axial Wall....74
5.1.2.5 Depth of Occlusal Floor from Central Fissure 75
5.1.2.6 Cusp Reduction....77
5.1.3 PREPARATION CHARACTERISTICS 78
5.1.3.1 Gingival Margin in Dentine or Enamel....78
5.1.3.2 Margins Bevelled Occlusally or Gingivally 79
5.1.3.3 Opposing Tooth Contact at Restoration Margins 79
5.1.3.4 Angular Cavosurface Margins 79
5.1.3.5 Sharp Internal Line or Point Angles....80
5.1.3.6 Retention Boxes 80
5.1.3.7 Metal Reinforcement....80
5.1.3.8 Preparation Taper....81
5.1.4 EXAMINER RELIABILITY 81
5.1.5 LIMITATIONS OF THE STUDY 81
5.1.6 **DISCUSSION**....83
5.1.7 **CONCLUSIONS AND RECOMMENDATIONS** 87

5.2 SECTION TWO: RESTORATION FAILURES 89

5.2.1 INTRODUCTION 89
5.2.2 SAMPLE POPULATION 89
5.2.2a Gender 89
5.2.2b Age Range 89
5.2.2c Distribution of Restorations 90
5.2.2c1 Restoration Distribution in Male and Female Patients 90
5.2.2c2 Restoration Distribution in Maxilla and Mandible 90
5.2.2c3 Restoration Distribution With and Without Metal Reinforcement 91
5.2.2c4 Restoration Distribution by Operators 92
5.2.2d Reasons for Restoration Placement 92
5.2.2d1 Tooth-Related Reasons 92
5.2.2d2 Previous Restoration-Related Reasons 93
5.2.3 RESTORATION FAILURES 94
5.2.3.a Failure Types for Different Restorations 95
5.2.3b Failure Types for Different Age Groups 98
5.2.3c Failure Types for Operators 98
5.2.3d Failure Types for Bruxer and Non-bruxer Patients 99
5.2.3e Failure Types with Different Liners/Bases 100
5.2.3f Failure Types with Different Resin Composite Luting Agents 101
5.2.3g Failure Reasons and Treatments after Failures 102
5.2.3g1 Debonding 103
5.2.3g2 Bulk Fracture 103
5.2.3g3 Chip Fracture 104
5.2.3g4 Microfracture 104
5.2.3g5 Colour Mismatch 105
5.2.3g6 Pulpitis 105
5.2.3g7 Apparent Failure 106
5.2.4 EXAMINER RELIABILITY 106
5.2.5 LIMITATIONS OF THE STUDY 106

5.3 SECTION THREE: RESTORATION SURVIVALS 107

5.3.1: INTRODUCTION 107
5.3.2 RESTORATION SURVIVALS 108
5.3.2.1 Survival of All Restoration Types 108
5.3.2.2 Veneers With and Without Incisal Coverage 109
5.3.2.3 Onlays With and Without Metal Reinforcement 110
5.3.2.4 Shell Crowns With and Without Metal Reinforcement 110
5.3.2.5 Cantilever and Fixed-Fixed Bridges 111
5.3.2.6 Restorations Luted with Different Resin Composite Cements 112
5.3.2.7 Restorations in Patients with Parafunctional Habits 112
5.3.2.8 Restorations in Patients from Different Age Groups 113
5.3.2.9 Restorations in Male and Female Patients 113
5.3.2.10 Restorations by Arch Distribution 114
5.3.2.11 Restorations Placed by Different Operators 115
5.3.3 **DISCUSSION** 116
5.3.3.1 Introduction 116
5.3.3.2 Bulk Fracture 116
5.3.3.3 Post-Operative Sensitivity 122

5.3.3.4 Debonding *124*
5.3.3.5 Parafunctional Habits *125*
5.3.3.6 Age Distribution *126*
5.3.3.7 Arch Distribution *127*
5.3.3.8 Operators *127*
5.3.4 **CONCLUSIONS AND RECOMMENDATIONS** 128

REFERENCES 130

APPENDICES

I. Materials Details i
II. Proformas ii
III. Preparation Dimensions v
IV. Restoration Failures xxii
V. Life Tables Estimates .... xxx vii
VI. Examiner Reliability li

Summary

During the last decade, the demand by patients for tooth-coloured restorations has increased. Common problems associated with large resin composite restorations in general dental practice include wear, fracture, and secondary caries. Such problems have restricted their wide-spread use, especially in posterior teeth. Ceramometal restorations, on the other hand, require excessive tooth reduction and may also have aesthetic problems. These limitations resulted in the development of resin-bonded porcelain restorations. Porcelains are well-known as aesthetic and biocompatible materials, and can be a valuable alternative restorative material when appropriate case selection and indications for their clinical use are applied. Many in vivo and in vitro investigations of resin-bonded porcelain restorations have been reported in the literature. The aim of the present study was to investigate whether or not these investigations are relevant to private dental practice. For this purpose, the study was divided into three sections to:

1) Investigate the preparation designs used in a specialist private practice, and to compare the dimensions of the dies of fractured posterior single restorations (shell or full veneer crowns, and onlays) with those of similar intact restorations,

2) Determine the usual failure modes of resin-bonded porcelain restorations, and

3) Evaluate the survival rates of different types of such restorations in a comparative manner.

A total of 536 resin-bonded porcelain restorations were selected from a private practice in which two prosthodontists worked. The restorations comprised shell (full veneer) crowns (229), onlays (97), inlays (9), labial veneers without incisal coverage (64), labial veneers with incisal coverage (46), chip porcelain veneers (15), cantilever bridges (49),

and fixed-fixed bridges (27). Of these restorations, 103 posterior single shell crowns and onlays were selected to investigate preparation dimensions and designs. Measurements of different aspects of the preparations were taken from stone dies of the prepared teeth, for both intact and subsequently fractured restorations, and for restorations with and without metal reinforcement. Measurements were taken of the intercuspal width, isthmus width, height of axial wall, proximal width, depth of occlusal floor from central fissure, and working cusp reduction. Preparation characteristics such as preparation taper, retention grooves, margins finished in dentine or enamel, and type of finishing lines were also assessed.

The results of this study showed that the average porcelain thicknesses were often within the range of those generally recommended in the literature (1.5-2.0 mm). However, thicknesses less than 1.0 mm, and more than 4.0 mm, at the central fissures and over the working-side cusps, were also found following the removal of previous amalgam restorations, and extension of preparations into the access cavities of root canal filled teeth. Preparation dimensions tended to be slightly larger in the fractured restorations. No significant differences were found between the dimensions for shell crowns or onlays fabricated with and without metal reinforcement, although the dimensions of those restorations with metal reinforcement tended to be slightly larger. Preparation tapers were mostly between 21-40° for the intact restorations, and 10-20° for the fractured restorations. Large preparation convergences were more frequently observed after removal of amalgam restorations, but this did not compromise the retention of the restorations.

Of the 536 restorations, 123 (23%) failed. Bulk fracture comprised the highest number of failures recorded in this study (10.4%). Other restoration failures included debonding

(2.8%), pulpitis (2.8%), chip fracture (2.6%), microfracture (1.1%), colour mismatch (1%) and connector-fracture for bridges (0.6%). No recurrent caries was reported. Fixed-fixed bridges showed the highest failure rate (70%) followed by onlays (without and with metal reinforcement), chip porcelain veneers, shell crowns (without metal reinforcement), cantilever bridges, and then veneers without and with incisal coverage.

Restorations survivals were analysed using life table methods. The period covered by the study records was from 1988 to mid-1995. The overall survival of all of the restorations at the 75% quartile was 58.9± 6.2 months. The results of the survival analyses showed that labial porcelain veneers with incisal coverage showed a better survival than did veneers without incisal coverage. Shell crown restorations demonstrated a better survival than did onlays, but the difference was not statistically significant. Comparison of shell crowns and onlays fabricated with and without metal reinforcement showed that those with a metal substructure survived for slightly longer than did those without a metal substructure. Shell crowns and onlays placed in the maxillary arch had better survivals than those placed in the mandibular arch. Cantilever bridges showed significantly better survivals than did fixed-fixed bridges.

The results showed that porcelain restoration thickness was not the most significant factor determining the longevity of resin-bonded porcelain restorations, since many very thin and very thick restorations survived during the period of this study. However, bulk fracture, as expected from the physical characteristics of porcelain materials, was an important failure reason. The use of metal reinforcement of the porcelain in selected cases increased the clinical survivals of the posterior restorations.

CHAPTER ONE

Introduction

1.1 Introduction

Several recent publications have reviewed the alternatives to dental amalgam, principally in response to concerns about possible mercury toxicity from amalgam restorations, but also in response to the increasing emphasis now being placed on the use of more aesthetic dental materials by dentists, patients and the media, especially in Western Countries (The Dental Advisor 1992, ADA Council 1994, CRA Newsletter 1994, Leinfelder 1994, Tyas 1994, Burke and Qualtrough 1994, Christensen 1995).

A considerable number of sound, functional amalgam restorations have been needlessly replaced by, perhaps, less suitable alternative materials, with considerable loss of additional sound tooth substance. The biological consequences and cost-effectiveness of such alternative material treatments remain to be determined. Aesthetic and conservative functional aspects of restorative dental materials have been two important criteria used to determine the success of these materials.

An alternative to the use of conventional metallic and ceramometallic restorative materials for single restorations or bridgework, involves the use of porcelain or ceramic materials which are resin-bonded to tooth structure. The porcelain may also be fused to minimal metal substructures for improved resistance to fracture, and anterior bridge designs may be modified to reduce fractures at connectors. However, there is scant information in the literature on the long-term clinical performance of resin-bonded anterior and posterior porcelain restorations, apart from anterior porcelain veneers. Therefore, the present study evaluates the long-term clinical longevity or survival, and posterior preparation designs, of a large number of various types of resin-bonded porcelain restorations placed in a specialist private dental practice.

1.2 History of Restorative Materials

Dentists have conventionally divided restorative dental services into anterior and posterior restorations. Aesthetics and function have been the two most important aims of restorative dentistry for the anterior and posterior tooth regions, respectively. However, patients are now also increasingly interested in the aesthetic aspects of restored posterior teeth. But, finding an ideal posterior restorative material which satisfies both the long-term aesthetic and functional needs of patients has remained elusive.

1.2.1 Amalgam

Dental amalgam has been a posterior restorative material since the last century. The first amalgam used in dentistry more than hundred years ago was a combination of silver coin and mercury. A condensable mass which could be inserted into a cavity and then carved to the desirable shape were the most attractive characteristics of this material. Current amalgam alloys contain relatively high amounts of copper. This element confers less creep with less marginal fracture and ditching of the restorations, and less corrosion by the elimination of gamma 2 phase. Although dental amalgam has the advantages of low cost and ease of manipulation, and is clinically durable, it often results in subsequent tooth fracture because of its lack of adhesion, corrosive breakdown and dimensional changes. The material also releases mercury and it is unaesthetic.

1.2.2 Gold

For a long time, gold alloys have been one of the most ideal materials for the restoration of posterior teeth. They became more popular at the beginning of this century. Gold alloys contain varying amounts of gold, silver, copper, platinum, palladium and zinc depending on the different types of alloys (Type I to Type IV). Gold alloys are corrosion resistant, relatively easy to adjust and cement, and have excellent physical and mechanical characteristics. Nevertheless, their yellowish colour, high costs and technique sensitivity are disadvantages.

1.2.3 Resin Composite

The importance of aesthetics led to the introduction of resin composite materials to the dental profession in the 1960's. The first resin composites were not capable of restoring occlusal surfaces in the posterior teeth, due to their low wear resistance. Modifications to the original materials resulted in smaller filler particles (approximately 3μm average) and higher filler contents (75 - 80 wt%) which produced materials with more wear resistance. Despite the advantages of excellent aesthetics and ability to bond to tooth structure, their technical sensitivity, longer chairtime, higher rate of secondary caries and inadequate wear resistance made them unsuitable substitutes for large amalgam restorations. One major problem with resin composite is the polymerisation shrinkage of the material, which often leads to marginal leakage, post-operative sensitivity and the occurrence of secondary caries. To eliminate the problems caused by polymerisation shrinkage of resin composite, heat-cured resin composite was introduced by Wendt in 1987 (Garber and Goldstein 1994a). Heat-cured resin composite restorations allow better control of proximal contours and contacts, and better adaptation (especially at gingival margins) with better physical properties than with conventional resin composite restorations, but they are expensive and need more time and skill for fabrication. Resin composite material is still unsuitable for heavy load-bearing posterior restorations.

1.2.4 Dental Porcelain

One of the earliest inorganic materials which was known and changed by man, was ceramic. Its first use in dentistry goes back nearly 200 years ago. An Italian dentist made the first individual porcelain teeth in 1808. He never found any great success because his restorations were opaque and brittle (McLean 1974). Ceramics were not accepted in restorative dentistry until the introduction of fixed restorations in the late 19th century. It was in 1903 that Dr. Land first made a porcelain jacket crown (McLean 1974). By 1925, porcelain was broadly used in dentistry. At the same time, in Europe, high-fusing porcelains were introduced to the dental profession. During this period, iridioplatinum metal reinforcement for porcelain restorations was developed. The first gold alloys fused to porcelain restorations were developed in the USA. In 1963, McLean and Hughes introduced another method of reinforcing porcelain, the alumina reinforced crown.

The high expense of high-gold alloys led to the development of other alternative alloys such as Au-Pd-Ag, Pd-Ag, Ni-Cr, Ni-Cr-Be and Co-Cr in the 1970's (Anusavice 1993). The use of thinner metal copings (0.2-0.3 mm) of Ni-Cr or Ni-Cr-Be alloys, and construction of porcelain margins came into dentistry in the early 1980's to reduce the aesthetic problems of metal-porcelain margins for restorations. The relatively low strengths of the porcelain foil-crown systems are an obstacle for their application in the posterior regions of the mouth. The same problems with porcelain jacket crowns limits their use to the anterior incisors.

Although the first porcelain inlays were fabricated at the end of the last century, they had not been adapted for general use until recent years. The problems of high costs, firing shrinkage, susceptibility to failure under occlusal load, wear of opposing tooth structure, and the soluble cements then available made them unsuccessful.

These problems have been largely overcome by recent developments in reinforcing porcelain materials (high alumina core porcelain, prefabricated blocks of porcelain), together with the ability to etch and bond porcelain to tooth structure. These developments led to a new concept in restorative dentistry, etched-porcelain resin-bonded restorations. Etched-porcelain resin-bonded restorations were introduced to the dental profession nearly two decades ago. Aesthetics and the saving of tooth structure have been the two main goals for the use of these restorations. Long-term satisfactory clinical results have been obtained for gold and ceramometal or porcelain fused to metal (PFM) restorations. However, the appearance of the gold restorations, and the severe tooth reduction required for PFM restorations has promoted the recent interest in the resin-bonded porcelain restorations. Problems with other restorative materials, such as the metallic appearance and mercury release with amalgam, and the marginal discolouration, postoperative sensitivity, and wear for resin composite have also been major factors in this change of interest. This enthusiasm for resin-bonded porcelain restorations is not only for single restorations but also for fixed partial dentures.

Although resin-bonded fixed partial dentures supported by a metal framework save tooth structure, the prostheses are often unaesthetic.

Resin-bonded porcelain restorations restore lost tooth structure with the main aims of returning the natural form and appearance of the tooth, while conserving the existing tooth structure. Metal substructures may be used in these restorations. Therefore, there are two types of resin-bonded porcelain restorations: a) all-ceramic, and b) metal-reinforced porcelain restorations. The strength of these restorations relies on the type of porcelain materials used (In-Ceram, Empress, Optec-HSP), the restoration design, and the bond to tooth structure for the all-ceramic restorations; and metal substructure for the metal-reinforced types of restorations. In this system, a ceramic restoration (single or bridge) is bonded to a large area of enamel with a resin composite adhesive. The fitting surface of the ceramic restoration is usually etched with hydrofluoric acid. The resin composite adhesive is used to cement the etched porcelain restoration to the treated tooth structure (enamel and dentine). Silane coupling agents are used to produce appropriate bonds between the resin composite adhesive and the porcelain restoration.

Success of resin-bonded porcelain restorations depends on the technique and materials which are used in this system. Porcelain itself is a brittle material without the ability to withstand plastic deformation, which compromised its wide-spread use as a restorative material. However, if the deformation of porcelain is prevented, a strong material can be expected. This can be achieved in several ways. One is the use of a metal substructure which acts as a support and provides resistance to deformation in porcelain. In the presence of a strong bond between tooth structure and the porcelain restoration, dentine can also play the same role for porcelain as it does for enamel. The forces applied to the porcelain restoration are then transferred through the resin composite cement and distributed in the underlying dentine. As a result, no catastrophic damage is expected since the porcelain is no longer deformed. Another alternative is the use of a high strength porcelain (In-Ceram, Empress) as a core which supports a veneer of conventional feldspathic porcelain.

Attempts have been made to improve the quality of the materials used for the resin-bonded porcelain restorations. Inherent defects such as porosity (introduced during fabrication) and flaws (produced during the finishing process) are major structural parameters which lead to catastrophic fracture in porcelain materials. A solution to these problems is the use of a cast-glass ceramic material (Dicor). Murphy in 1937 (Roulet and Herder 1991a) was probably the first dentist to melt glass onto a platinum sheet that had been burnished in the cavity preparation. Glass-ceramic in general is a crystallised glass and shows properties of both crystalline and glass materials. The casting is obtained as a transparent glass. It is amorphous and fragile. Through a single-step heat treatment (ceramming) at 1,075^{o} C for 6 hours, the cast glass bodies are converted to a semicrystalline phase. The structural change brings a small decrease in volume which is compensated for by the expansion of the investment material of the glass-ceramic casting. Hence, restorations should fit better than those made from conventional dental porcelains (Roulet and Herder 1991a). However, colour mismatch, the need for special equipment, and technique sensitivity are disadvantages of the system.

A newer alternative of the all-ceramic type is the pressed glass ceramic system (IPS/Empress). Two basic glasses are involved in the manufacturing of IPS/Empress. An amorphous glass is changed to a dispersed microcrystalline phase (leucite) during processing. Fabrication is based on the injection moulded technique. The material has a very high flexural strength which makes it strong enough to be used in all-ceramic restorations. The marginal fit and colour match appear better than for Dicor (Garber and Goldstein 1994a). Nevertheless, IPS/Empress is expensive and needs special equipment.

A high strength alumina core ceramic material with a glass infiltrated core (In-Ceram) has a very high flexural strength. It supports a veneer of feldspathic porcelain in a similar manner to the metal coping in a PFM restoration. Alumina particles of 3.8 μm size prevent crack propagation through the porcelain material. It is strong enough for anterior 3-unit fixed bridges in selected cases, and also for posterior single crowns. The crowns are rather opaque and difficult to etch because of the high alumina content of the cores.

Optec-HSP is a high strength feldspathic porcelain which is not a core material. It gains its strength from the growth of leucite crystals ($KAlSi_2O_6$). It has been used for bonded inlays, onlays, crowns and veneers.

Mörmann and Brandestini (1989) developed a computer aided milling system (CAD/CAM) to make ceramic reconstructions (Cerec), to produce inlays from ceramic materials at the chairside, in one appointment. The cavity is stereophotogrammatically scanned immediately after the preparation has been made. A ceramic inlay is then shaped, according to this scanning, by a microprocessor. The restoration's occlusal morphology cannot be programmed and must be ground after permanent cementation. In contrast to Europe, where a feldspathic ceramic block is generally used (Vita-Cerec Mark II), the ceramic material generally used in the USA is a glass-ceramic block. Machinable glass-ceramic for dental CAD/CAM application (Dicor/MGC) has been developed with the crystal growth regulated by a specific heat treatment; the resultant microstructure is fine-grained, homogeneous, non-porous, and uniform in size (Roulet and Herder 1991a). A single appointment only, no impression needed, less fracture incidence, and wear and hardness similar to enamel are the advantages of the system. Colour mismatch, wear of the resin composite cement and consequently, marginal fracture of the porcelain are clinical problems associated with the technique.

Another alternative is the Celay (Mikrona) system in which a mouldable resin composite material is directly shaped in the inlay cavity preparation inside the mouth. Any occlusal or contact adjustments can be done at this stage. The material is then light cured before removal from the mouth. This pre-inlay acts as a model which can be copied to produce a ceramic restoration. This system provides restorations with better marginal fit than the Cerec system and the processing time is very short (three minutes for a small inlay), (Garber and Goldstein 1994a). An extensive review of the literature on direct-milled dental restorations has been published recently (Kelly 1995).

CHAPTER TWO

Literature Review

2.1 Literature Review

Although some investigators have reported clinically-acceptable results for posterior resin-bonded porcelain restorations (Jensen 1988, Isenberg et al. 1991, Mörmann and Krejci 1992), there are still some problems associated with the use of these restorations. Marginal seal is one of the most important criteria in evaluating the success of restorations, and the characteristics of the different materials used in the construction of resin-bonded porcelain restorations are of significant importance.

2.1.1 Marginal Adaptation

Various techniques (dye and radioisotope penetration, scanning electron microscope, light microscope), have evaluated marginal seal and adaptation of ceramic restorations to the cavity walls. Visual assessment of the restoration and cavity margins by scanning electron microscopy (SEM) or by light microscopy is one of the techniques which has provided valuable information.

Studies by Weaver et al. (1991), Qualtrough et al. (1991) and Olin et al. (1992) revealed a deterioration of the margins after thermocycling, especially at the enamel/resin composite interfaces. It was shown by Krejci et al. (1993) that the initial percentages of continuous margins in enamel exceeded 90%. However, marginal integrity again deteriorated after thermocycling. A mismatch of the coefficient of thermal expansion between the tooth and restorative materials was responsible for this effect.

The marginal fit of resin-bonded porcelain restorations was assessed by several authors using dye or isotope penetration techniques. Tjan et al. (1989) studied the marginal fit of Dicor and Cerestore veneers to enamel and dentine before and after thermocycling. Their results revealed greater microleakage at the dentine/composite lute than at the enamel/composite lute interfaces. The same results were achieved by Shortal et al. (1989), Zaimoglu et al. (1992) and Reid et al. (1993). Because of its higher inorganic components, a better etch pattern of the enamel is responsible for a more durable bond between the enamel and resin cement, in comparison with dentine. The role of dentine bonding agents (DBAs) in eliminating marginal leakage was tested by Tjan et al. (1989). It was concluded that the DBAs used were not strong enough to produce gap-free margins at the dentine interface. The authors also showed significantly less microleakage with Dicor crowns than with Ceramco II samples. The authors suggested that the higher bond strength between Ceramco II and resin cement produced higher destructive forces at the tooth/resin cement interfaces and, consequently, more gap formation. In one study, the effect of DBAs on marginal adaptation of bonded tooth-coloured inlays was examined before and after thermocycling (Klaiber et al. 1994). Class II cavities with the margins in dentine were prepared on extracted human molars. The inlays were made of a heat-pressed glass ceramic (IPS/Empress), and a fine hybrid resin composite (Brilliant). The dentine adhesives used in this study included A.R.T. Bond, All Bond 2, and Syntec. From the results of this study, it was concluded that the marginal adaptation of laboratory made inlays was improved by some of the new DBAs (All Bond 2).

Sorensen et al. (1991a) and Ferrari (1991) demonstrated less dye penetration in etched and silanated samples in comparison with untreated samples. The latter study using glass-ionomer cement (GIC) or resin composite cement showed the deepest dye penetration in the samples luted with GIC. This confirmed the previous findings by Shortal et al. (1989). In this study, it was shown that polymaleic acid-based cements were more soluble than polyacrylic acid-based cements. Therefore, GIC is affected adversely by early exposure to moisture, and even varnishes do not completely protect a freshly-set auto-cured GIC. Lacy et al. (1992) compared the marginal seal of porcelain (G-Cera) and resin composite (Visio-Gem) veneers finished at enamel or dentine, or at previously-placed GIC restorations. They used different DBAs such as Tenure Solution, Mirage Bond, Gluma, Scotchbond Dual-Cure, and Scotchbond 2. The best marginal seal was found in porcelain veneers bonded to enamel. Among the porcelain and resin composite veneers bonded to dentine, Visio-Gem showed extensive leakage. All veneers placed over the GIC restorations had higher amounts of leakage.

Sorensen et al. (1992) found that microleakage at the cervical tooth margins was more than at the incisal margins. This finding was in agreement with another study by Zaimoglu et al. (1992). The authors explained these results as being caused by the different directions of the enamel prisms in the cervical region.

In one study (Olin et al. 1992), the effect of fatigue stresses on veneer restorations was tested, and microleakage was observed in the thermocycled teeth only. This study also indicated that the microleakage was apparent at the enamel/resin interfaces, with no dye penetration at the porcelain/resin interfaces. This latter phenomenon had been also observed by Shortal et al. (1989) and Sorensen et al. (1992). Rougher irregularities created on the etched porcelain than on the etched enamel may explain these findings.

The cement itself is another factor affecting marginal integrity. Van Meerbeek et al. (1992) reported more submargination wear for hybrid resin luting cements than for microfilled cements used with CAD/CAM restorations. This finding was later confirmed by many other authors including O'Neal et al. (1993) and Kawai et al. (1994). In addition, the latter studies demonstrated that the vertical loss of cement (wear) increased linearly with the marginal gap width.

Zaimoglu et al. (1992) showed the effect of polymerisation shrinkage and thermal dimension change of resin composite cements on microleakage and debonding of bonded porcelain restorations. They demonstrated that incomplete polymerisation of resin composite cement led to pulp damage and debonding in bonded porcelain samples. Strang et al. (1987) indicated that the polymerisation of resin composite cement was affected by porcelain thickness, shade and opacity. However, Linden et al. (1990) found that unlike thickness and shade, porcelain opacity had little effect on the polymerisation of resin composite cement. Fleiter et al. (1992) recommended the use of light cure resin composite cements in porcelain restorations less than 1 mm. The type of porcelain is important in polymerisation of resin composite cement. Blackman et al. (1990) found that with the same thickness of porcelain, both light cure (Porcelite) and dual cure (Dual-Cure Dicor) cements cured better under Dicor samples than under Vita VMK 68 samples. Thin ceramic specimens showed a highly-cured state for all cement/ceramic combinations.

The following statements can be summarised from this review:

1) There is general agreement that metal crown margins can fit better than porcelain crown margins. Among porcelain materials, those which are pressed directly on a die may give a better marginal fit.

2) Marginal opening increases after cementation and thermocycling. It is apparent that cement thickness affects marginal integrity.

3) As expected, porcelain margins terminated on enamel fit better and are more durable than those terminated on dentine.

4) Etching enamel and treatment of the fitting surfaces of porcelain restorations with a silane coupling agent (SCA) decreases microleakage.

5) Cervical margins show more microleakage than incisal margins.

6) A higher rate of microleakage is observed at the tooth/resin cement interfaces than at the porcelain/resin cement interfaces.

7) Microfilled resin composite cements wear less than hybrid cements. A direct relationship between wear and marginal gap width has been shown.

2.1.2 Bond Strength

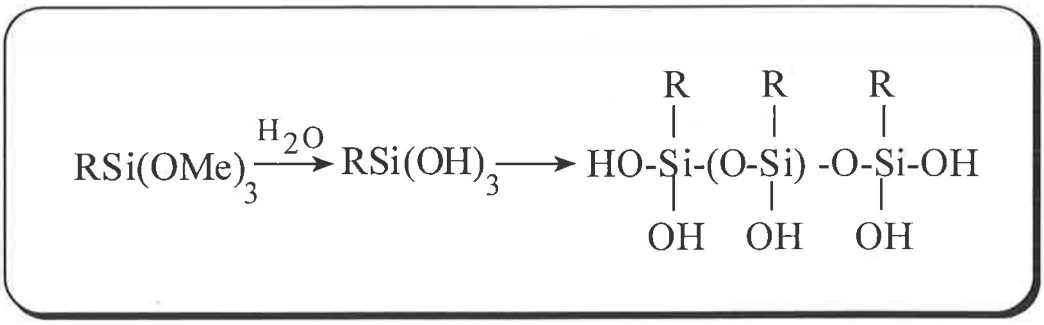
In the early 1970's, several reports suggested the use of acid-etched resin-bonded bridges as an alternative to removable prosthodontic appliances. The bond strength of this type of acid-etch bridge has been studied. The first pontics for these bridges were natural teeth or plastic denture teeth which were bonded with resin composite to the adjacent teeth. The method of etching porcelain to improve bond strength was introduced by Simonsen and Calamia (1983). They examined the effect of different etching times on bond strength and found that the strength increased as the etching time increased. Another study by Hofmann and Haller (1991) confirmed this result. By contrast, a study by Nathanson et al. (1992) showed that increased etching time did not improve the bond strength of ceramic inlays to extracted teeth. Later, Calamia et al.

(1987) also reported a stronger bond with 2.5 minutes of porcelain etching than with 20 minutes.

The idea of etching porcelain to improve the bond between resin cement and porcelain derived from etching enamel or dentine for resin composite restorations. In addition, the presence of a coupling agent, which produces bonds with either porcelain or resin, has been shown to improve the bond strength of etched-porcelain resin-bonded restorations. The role of these two factors has been investigated by several authors. One of the earliest studies by Stangel et al. (1987) revealed that silane coupling agents significantly improved the porcelain to resin bond. A stronger bond was recorded in this study when a combination of porcelain etching and silane treatment was applied. A markedly stronger bond was observed in silane-treated samples as compared with nonsilanated samples by Stacey (1993).

Stokes et al. (1988), Tjan and Nemetz (1988), and Bailey and Bennett (1988) all demonstrated an enhanced bond strength when silane, or when a combination of silane and etching were applied to the porcelain surfaces. In contrast to these studies, Sorensen et al. (1991b) and Jong et al. (1992) found that, although etching the porcelain surfaces improved the bond significantly, the application of a coupling agent to etched porcelain did not improve the bond. The application of rigorous stresses by thermocycling to the samples in these two latter studies, as compared with the previous studies, may account for the different results.

A requirement for a coupling agent to act as a biproduct molecule is the hydrolysis of the silane monomers (Equation 1). The more the monomers are hydrolysed, then the more siloxanol groups ($RSi(OH)_x$) that are produced and, consequently, the more bonds that will be created between OH groups of the coupling agent and porcelain surface (Plueddemann, 1991):



Equation 1: Hydrolysis of silane coupling agent (Plueddemann 1991)

The results from a study by Pratt et al. (1989) confirmed this fact. They reported a cohesive failure present in the porcelain samples when the silane had the highest degree of hydrolysis.

The ionic bond at the mineral interfaces (porcelain/coupling agent) is based on an equilibrium condition (Equation 2). This bond is hydrolysed during exposure to water, but is reformed when dried (Plueddemann 1991):

$$\text{M-O-Si-} + H_2O \rightleftharpoons \text{M-O-H} + \text{H-O-Si-}$$

Equation 2: Equilibrium condition between silane coupling agent and mineral surface (Plueddemann 1991)

Pratt et al. (1989), Diaz-Arnold et al. (1989), and Roulet and Soderholm (1992) observed a general decrease in bond strength after water storage of silanated porcelain samples. However, Bailey and Bennett (1988), and Diaz-Arnold and Aquilino (1989) showed no decrease in bond strength after water storage. The difference between the results may be explained by the difference in duration of water storage or the type of silane agent used (heat or chemical cured). Bailey and Bennett (1988), and Roulet and Soderholm (1992) demonstrated that the bond strength loss of a chemical-cured silane agent was higher than that of a heat-cured type after one year. In respect to an existing equilibrium condition in the bond between porcelain and silane coupling agent, removing the extra water from the surface may be responsible for more durable bonds in the samples treated with a heat-cured silane. However, Barghi and Berry (1994) stated that heat treating of silane may not affect the bond strength. Most investigators have stated that degradation of the bond is time dependent. For example, Pratt et al. (1989) observed early cohesive failures in porcelain samples subjected to a shear stress, whereas adhesive failures increased over time. Chang et al. (1994) found no significant bond strength differences in enamel and cast-glass ceramic (Dicor) samples when different types of resin composite cements (Twinlook, Optec, Clearfil) were used.

Different etchants and surface treatments of porcelain have been shown to affect bond strength. Some authors have compared the strength of samples etched with HF or NH_4HF_2. Lacy et al. (1988), Bailey and Bennett (1988) and Hofmann and Haller (1991) found no significant difference between these two etchants. By contrast, Nathanson et al. (1992) reported a greater bond strength with HF than with NH_4HF_2.

As previously mentioned, Stokes et al. (1988) claimed an increase in bond strength when a SCA was applied. This study also indicated that the roughened and silanated porcelain samples had greater bond strengths than the glazed and silanated samples. Other research by Cochran et al. (1988), Lacy et al. (1988), Diaz-Arnold et al. (1989), and Hosokawa et al. (1995) were in agreement with the former study.

A comparison of etched and roughened porcelain samples showed higher bond strengths with the etched samples (Wolf et al. 1992). A significant correlation between bond strength and average roughness was found for the etched samples, but not for the sandblasted samples in this study.

Clinical success with adhesive porcelain restorations has been assisted by the ability to develop a reliable bond of resin composite to the etched porcelain surfaces. The irregularities which are created by etching are an essential factor in the bond strength of the adhesive restorations. Therefore, the porcelain material itself is important in determining the magnitude of bond strength. Chan et al. (1987) and Sörensen et al. (1991b) examined the bond strengths of different types of porcelain materials. A stronger bond was reported to the feldspathic porcelain than to the aluminous porcelain. The authors related this result to the poorly-etched surface of the aluminous porcelain. Tjan and Nemetz (1988) showed that the larger porosities and irregularities of the Ceramco II samples created stronger bonds in comparison with the finer-grained surfaces of etched Dicor samples.

Deterioration of the bond over time has been reported by several authors. Bailey and Bennett (1988), Diaz-Arnold et al. (1989), Burkett et al. (1992), and Stacy (1993) all demonstrated a general decrease in bond strength after thermocycling. Different coefficients of thermal expansion between resin composite and porcelain, and resin composite and tooth contribute to the weakening of the bond.

It has been shown that the bond to enamel is stronger than that to dentine. Tseng et al. (1992) compared the bond strength of resin-bonded porcelain samples to enamel and dentine using dentine bonding agents (DBAs). The enamel bond was markedly stronger than the dentine bond. Among samples luted to dentine, those which had been thermocycled demonstrated lower bond strengths. The capacity to produce a strong and durable bond to dentine is a most desirable property in a restorative resin. The smear layer covers the dentinal tubules and prevents penetration of resin monomer into the tubules. Bond strengths of resin composite to the etched dentine are generally not as strong as those to the etched enamel. It may be concluded that to obtain a reliable bond to dentine, the application of a dentine bonding agent is necessary (Asmussen and Munksgaard 1988). Kumatsu and Finger (1986) evaluated the role of DBAs on bond strength and marginal gap of restorative resins. They found that the application of a dentine adhesive to a dentine smear layer was unfavourable. The smear layer was a barrier reducing the chance of bonding to the underlying dentine. But, removal of the smear layer increased dentine permeability, resulting in postoperative sensitivity.

Tagami et al. (1990) demonstrated that the superficial dentine was less permeable than the deeper dentine. This may be due to an increase in either tubule diameter or tubule density in deep dentine. In addition, the bond strength of resin composite to deep dentine was lower than that to superficial dentine. The authors explained this in terms of there being fewer calcium ions available in the deep dentine for chemical bonding, and by the difference in microporosities present in deep and superficial dentine. Since cavity preparation includes both superficial and deep dentine, the resin composite is attached to the superficial dentine but is pulled away from the deep dentine, leaving a gap. Therefore, to prevent gap formation, the early bond strength must exceed the forces of polymerisation shrinkage of the resin composite (7-9 MPa). Most of the DBAs did not produce early bond strengths greater than the polymerisation contraction of the resin composite (Tagami et al. 1990), resulting in breaking of the marginal seal. Current DBAs have improved bond strengths to moist dentine. An in vitro study by

Øilo et al. (1990) showed that water storage and thermocycling significantly reduced the bond strength of DBAs.

Since porcelain materials are brittle, an adhesive cement is recommended to prevent bulk fracture of the material. Although both resin composite and glass-ionomer cement (GIC) give good adhesion to tooth structure, they differ in their adhesion to porcelain. Höglund et al. (1992) revealed an adhesive failure at the lute/porcelain interface in the GIC groups, while failure in the resin composite groups was cohesive. McInnes et al. (1989) reported greater bond strengths to Dicor and etched enamel with resin composite cement than with GIC. They also found that the bond of resin composite to untreated dentine was stronger than that of GIC. However, the advantage of GIC was shown in producing a more satisfactory seal in the gingival areas of approximal boxes of the cavity preparations.

The statements obtained from this review are listed as:

1) Etching the porcelain surface improves the bond. Although it has been shown that a greater bond may be achieved with longer etching times, a distinctive and optimal etching time for each material seems to be more effective than merely shorter or longer etching times.

2) Most investigators have demonstrated an increase in bond strengths when the combination of a coupling agent and an etchant is applied. Hydrolysis of the bond between the coupling agent and porcelain surfaces results in a reduction of the bond after long-term water storage and thermocycling.

3) There is no significant difference between HF and NH_4HF_2 in producing a stronger bond. Ammonium bifluoride, however, has been shown to be less dangerous clinically, and to be especially suitable for etching glass-ceramic materials.

4) Thermocycling weakens the bond between tooth/resin composite and resin composite/porcelain surfaces.

5) Adhesive luting agents produce stronger bonds in resin-bonded porcelain restorations. The samples luted with a resin cement have greater bond strengths than those luted with a GIC.

6) Bond strengths of resin restorative materials to enamel are stronger than those to dentine. The bond strengths of DBAs show long-term deterioration after water storage and thermocyling. Bond strength to the superficial dentine is stronger than that to the deep dentine.

2.1.3 Preparation Design

Porcelain materials are brittle when unsupported and they fracture easily under tensile stress. It has been shown by many authors that occlusal stresses, type of cement (bonded or non-bonded), and preparation design influence the strength and longevity of porcelain restorations.

The effect of preparation design on the strength of all-ceramic crowns was evaluated by Friedlander et al., Munoz et al., and Doyle et al. (1990) in a three-part study. They evaluated different finish lines and occlusal convergency angles, and compared the all-ceramic crowns with PFM crowns. The results of the three studies demonstrated that crowns prepared with higher occlusal convergency angles (15°-20°) were significantly stronger than those with a 5° convergency. More tapered preparations produced thicker crowns, resulting in stronger restorations. However, with regard to the pulp size, a high convergency angle was not recommended. It was shown that a 10° occlusal tapered preparation was the best compromise. The shoulder finish line produced the strongest restorations in the all-ceramic crowns. Friedlander et al. (1990) also demonstrated that with shoulder porcelain the crowns were seated against a flat surface. Therefore, there may be less lateral stress generated during occlusal loading than occurs with the cervically inclined surfaces of a chamfer finish line. A chamfer finish line with 0.8 mm deepness produced stronger crowns than with 1.2 mm tooth reduction.

Evaluation of specific preparation designs has been performed by several authors. Anusavice and Hojjatie (1988) examined three all-ceramic designs by 2-dimensional finite element analysis, and compared these designs with a PFM crown. Higher stresses occurred in the ceramic and cement layer in the all-ceramic crowns as compared with the PFM crown. They also found that the amount of incisogingival reduction did not influence the stress distribution in the crowns or cement. The results showed that the orientation of the applied load was a significant factor in stress distribution. The maximum stress values were obtained when the load was applied horizontally to the crowns.

Another study by the same authors (1992) indicated the role of crown thickness on the magnitude of the tensile stress. They employed finite element analysis to evaluate stress distribution on three crown designs loaded with horizontal and vertical forces of 200 N. They showed that the tensile stress induced in the thicker crowns (1.5 mm) was much smaller than that in the thinner crowns (0.5 mm). This difference in tensile stress was significant for the distributed load, in comparison to the concentrated load. Considering the role of crown flaws and cement voids, the results of the study demonstrated that the tensile stresses in no-flaw/no-void crowns were significantly lower than in the flaw/void condition.

In an evaluation of different designs for laminate veneer restorations, Highton et al. (1987) examined the effect of different tooth preparations on the strength of the veneers. They demonstrated an increase in the resistance to fracture area, and a decrease in the concentration of stresses in the veneers with coverage of the incisal edge. They stated that facial, incisal and gingival reduction provided suitable stress distribution. A study by Watanabe et al. (1992) using the finite element analysis method also showed the greatest tensile and compressive stresses in veneers without incisal coverage, and the least in the veneers with incisal coverage (half way down on the lingual surface).

Hui et al. (1991) examined four different veneer preparations. The preparations were window, overlay preparation, feathered incisal, and no preparation. It was demonstrated that the forces required for veneer failures were higher for the window preparation, because this preparation distributed the stresses similarly to the unprepared tooth. They also found that the forces at fracture were not statistically related to the thickness of the restorations, which was in agreement with the results of the study by Anusavice and Hojjatie (1988).

In a study by Kern et al. (1994) on fixed partial prostheses fabricated with In-Ceram as a core ceramic veneered with Vitadur-N, two types of preparations were examined. In this study, the fixed partial prostheses were made to replace a maxillary central incisor, on extracted human teeth. Two designs for the abutments were considered: 1) a minimal veneer preparation on the palatal surface and a small dimple in the cingulum, and 2) the same as for preparation 1, but with an additional box preparation proximal to the pontic. Their results showed that the fracture strength of restorations were significantly higher when proximal box preparations were added. They also found that, although adding more retentive preparation to the teeth strengthened the restorations, it weakened the tooth structure. For this reason, fractures of enamel and/or part of the abutment tooth were observed in 37.5% of the cases.

Pospiech et al. (1994) determined the influence of load orientation (45°, 60°) and the design of the interproximal connector on stress distribution in the In-Ceram fixed partial prostheses. They stated that since the average tensile strength of In-Ceram is 340 MPa, an all-porcelain resin-bonded fixed partial prostheses could be recommended if the height of the connector is a minimum of 4 mm, with rounded edges and little interdental separation.

Preparation designs for resin-bonded ceramic inlays and onlays have generally been based on those for cast alloys, but with greater bulk of ceramic material and usually slightly more taper than for the metal castings (Banks 1990, Roulet and Herder 1991b, Ubassy 1992, Broderson 1994, Garber and Goldstein 1994b). In addition, limitations of cutting instrumentation may dictate the preparation designs for direct milled ceramic restorations (Jedynakiewicz and Martin 1993). Design aspects will be covered further in the Discussion section.

From this review of the literature, one can conclude that:

1) In all-ceramic crown preparations, a greater occlusal convergency angle creates thicker restorations which are stronger.

2) Crown preparations with a shoulder finish line produce stronger restorations. Among crowns with a chamfer finish line, those with less tooth reduction (less inclined surface) result in stronger crowns.

3) In the preparation of veneer restorations, some authors negate the role of veneer thickness on the strength of the restoration. These authors believe that the orientation of

the applied load is more important than the veneer thickness. Some other investigators showed that the induction of tensile stresses on thicker veneers is smaller than on thinner veneers. This difference is only significant in the case of the application of distributed load.

2.1.4 Porcelain Strength

Progress in dental porcelain technology is limited by the inherent problems of these materials, such as their low tensile strength, and brittleness. All dental porcelains tend to fail at the same critical strain of the order of 0.1% (McLean and Kedge 1987). For this reason, increased strength and toughness can be achieved by an increase in the elastic modulus. Resistance to fracture and microleakage are probably the most important factors that influence the durability of porcelain restorations. The principal physical characteristics of porcelains are their high resistance to compression compared to their low resistance to flexure and tension (Dietschi et al. 1990). Because porcelains do not have any appreciable plastic deformation, gross fractures occur without any warning and advance across planes of maximal tensile stress.

Flaws and porosities in the porcelain material introduce cracks and lead to fracture. Flaws can occur on the edges, surfaces, and within the material, and might grow by stresses to initiate fracture. The flaws may be formed during surface grinding or from abrasion in service. Large pores can result from the burnout of organic impurities, or a non-uniform shrinkage during densification. From fracture mechanics, a relationship is obtained between the behavioural properties of strength (σ), fracture toughness ($K_{IC} = (2E\gamma i)^{0.5}$), and the structural characteristic of flaw size:

$$\sigma = \text{Constant} \times K_{IC} \times C^{-0.5} = \text{Constant} \times (2E\gamma i)^{0.5} \times C^{-0.5}$$

where the constant depends upon the structural characteristics of the flaw and how the ceramic is loaded, E is Young's modulus, and γi is the effective surface energy for fracture initiation (Messer et al. 1991). Fracture toughness (K_{IC}) is a measure of the strain-absorbing properties of brittle materials. It actually relates to the tensile stress that must be exceeded at the tip of a crack before catastrophic failure occurs (Rosenstiel and Porter 1987). Therefore, the first step in understanding the strength behaviour is to determine the fracture origin, and if possible, the flaw size.

Different methods have been introduced for strengthening of porcelain materials. McLean and Kedge (1987) stated that porcelain may be strengthened by dispersing ceramic crystals of high strength and elasticity in the matrix (Table 1). Alternative approaches to create greater strength include closure of pores (CAD/CAM systems which use dense, monolithic ceramic blocks).

Table 1: High strength ceramics (McLean and Kedge 1987)

Type of Porcelain	Flexural Strength (MPa)
Hot-pressed silicon nitride	800-900
Hot-pressed silicon carbide	400-750
Partially stabilised zirconia	640
High alumina, 98% purity	420-520
Cerestore nonshrink alumina ceramic	125-130
Dicor castable glass ceramic	140-150
Alumina core porcelain	125-150

The flexural strength of porcelain materials has been investigated from different aspects. The use of a rigid substructure, such as metal or high-strength ceramic often improves the strength of the weaker veneer porcelain. A primary comparison of the strength of all-ceramic systems to conventional metal-ceramic restorations has provided useful information about the ability of the all-ceramic systems to resist clinical failure. Campbell (1989) examined the strength of some ceramic materials (Hi-Ceram, Dicor, Cerestore, Optec), a conventional porcelain jacket crown (Vitadur), and some veneered metal-ceramic alloys. As was expected, the veneered metal alloys were stronger than the other groups. He also showed that none of the ceramic materials was as strong as the veneered metal alloys. A significant relationship was found between the flexural strength of the specimens and modulus of elasticity (E) of the substructure materials. The strength of the veneered specimens increased as the modulus of elasticity of the substructure increased. This implies that the rigidity of the substructure plays an important role in the strength of the veneered porcelain.

Following these findings, other investigators paid attention to the effect of the modulus of elasticity and the fracture toughness of the porcelain materials on their strength. Rosenstiel and Porter (1987) compared the K_{IC} of Vita VMK-68 discs with metal-ceramic crowns. E/hardness ratio and fracture resistance of the metal-ceramic crowns were significantly higher than that of the porcelain discs. Castellani et al. (1994) evaluated the fracture resistance of three types of all-ceramic crowns and compared these to the fracture values of metal-ceramic (PFM) restorations. Materials tested in this study were glass-ceramic (Dicor), aluminous-core porcelain (Hi-Ceram), and glass-infiltrated aluminous-core porcelain (In-Ceram). They demonstrated that the PFM specimens had significantly higher fracture resistance than the Hi-Ceram and Dicor samples. No significant difference between the metal-ceramic and In-Ceram specimens was found. The all-ceramic specimens showed catastrophic fracture, and cracks were visible through the entire thickness of the samples. The metal-ceramic samples on the other hand, showed superficial cracking that affected only the ceramic layer, sometimes with a few chips.

Rosenstiel and Porter (1989) measured the fracture toughness (KIc) of Dicor, Cerestore, Hi-Ceram, Renaissence, and Vitadur-N according to the equation:

$$K_{Ic} = 0.016\,(E/H)^{1/2} \times (P/Co^{3/2})$$

E/H is the elastic modulus to hardness ratio, P is the peak load, and Co is the crack length which is produced by a Knoop indenter. E/H ratio was calculated from the formula: $b'/a' = b/a - \alpha\, H/E$, where b'/a' is the ratio of the diagonals of indentation, b/a is the ratio of the diagonals of the indenter, and $\alpha = 0.45$. The results of this study showed that the fracture thoughness of the Dicor restorations was greater than that of the other restorations.

As previously mentioned, one method to strengthen porcelain materials is by dispersing high strength crystals in the material. These crystals help prevent propagation of microcracks. Hondrum and O'Brien (1988) examined the effects of two types of dispersed-crystals (aluminium oxide core and magnesium oxide core) on the modulus of rupture of Vitadur-N and Ceramco. Since there was a belief that the removal of the foil after construction of the all-ceramic crown may initiate microcracks on the internal surface of the core, the authors evaluated the strength of the cores with and without foil. Another theory which was tested in this study was the effect of the application of glaze to the internal surface of the cores. It had been theorised that the glaze reacts with the core material to further crystallisation, and can place the surface of the core in a compression condition. Therefore, the strength of the core material is enhanced. The results demonstrated that removing the platinum foil following by glazing the internal surfaces of the alumina core crowns (Vitadur-N) did not increase their fracture strength. However, glazing the magnesia core crowns (Ceramco) improved their fracture strength. The effect of leaving the foil on the strengths of both aluminium oxide core and magnesium oxide core crowns was not significant. The authors mentioned that the different results found between Vitadur-N and Ceramco were due to the porosity of the materials and the ability of the magnesium oxide core to absorb the glaze.

Seghi et al. (1990) evaluated the modulus of rupture (MOR) of different reinforced and non-reinforced materials. The MOR was achieved from the equation:

$$MOR = 3WL/2bd^2$$

where W is the breaking load in newtons, L is the test span in mm, b and d are the width and the thickness of the specimen in mm, respectively. The materials examined in this test were: a) Excelco, Ceramco II, Vitadur-N, Vita VMK-68, Mirage and Cerinate, which are all non-reinforced feldspathic porcelains, b) Vitadur-N (core) Hi-Ceram (core) and Dicor, which are a reinforced porcelain and glass-ceramic. Both of the reinforced materials produced significantly higher flexural strength values than did the conventional feldspathic porcelains. This finding confirmed an increase in the modulus of elasticity and, therefore, the flexural strength of crystalline-reinforced porcelain vs. conventional porcelain.

Scherrer et al. (1994) compared the fracture resistance of all-ceramic crowns cemented on extracted molar teeth with the fracture resistance of enamel in intact extracted teeth.

The all-ceramic crowns were made of Ceramco (feldspathic), Dicor (glass-ceramic) and In-Ceram (core, alumina-infiltrated glass veneered with Vitadur). The results showed that intact extracted teeth were significantly stronger than all-ceramic crowns. The highest fracture resistance among the all-ceramic groups was observed for the In-Ceram crowns. Kelly et al. (1994) examined the fracture surfaces of seven clinically-failed In-Ceram fixed partial prostheses, using light and electron microscope methods. In all cases, failures originated from the connector, and for five of the cases from the core-veneer interface. They also used finite element analysis, and indicated that: 1) veneering the connector surface seriously degraded load-bearing capacity, 2) high E was a more important design factor for the core material than high strength, and 3) stress failures arose due to abutment rotation.

Studies of inhomogeneous and microstructural defects related to porcelain fabrication have led to significant advancements in ceramic engineering. Kelly et al. (1989) examined the fracture surfaces of some Dicor and Vitadur-N bars to understand failure mechanisms, and the source and elimination of strength-limiting flaws, by fractography. In their article, a typical fracture-surface diagram of a glass was presented (Fig. 1). Glasses, glass-bonded ceramics, and fine-grained polycrystalline ceramics show this fracture feature. Coarse-grained polycrystalline ceramics and weaker multiphase ceramics do not reveal such a characteristic.

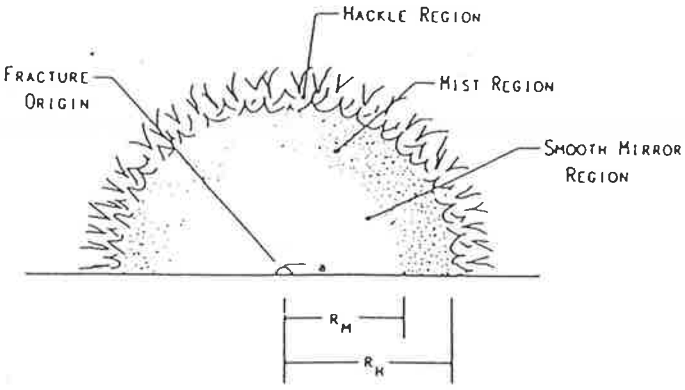


Figure 1: Typical fracture-surface feature (Kelly et al. 1989)

As can be seen in the figure, three major regions are distinguished:

1) The 'smooth mirror region' which is produced by slow crack growth during initial material failure.

2) The 'mist region' at which any increase in strain and kinetic energy increases the velocity of the crack. At terminal velocity, further increase in the strain and kinetic energy will not increase the crack velocity, but will nucleate additional microcracks at the crack tip. These microcracks do not have enough energy to propagate.

3) 'Hackle region' where the cracks extend into uncracked regions, and additional energy allows the growth of secondary cracks.

A relationship between fracture stress and fracture mirror radius is shown by the equation:

$$\delta = Ar^{-0.5} = \phi K_{IC} / \sqrt{1.2\pi}\ (c/r)^{0.5}$$

δ= Fracture stress, r= Mirror radius, A= Mirror constant, ϕ= Geometric constant, and c= Flaw size. Therefore, fractography can provide two important items of information: 1) identification of the source of failure, and 2) calculation of the stress at the failure point. With respect to the previous equations, Kelly et al. (1989) found that the fracture toughness and the modulus of rupture values of the Dicor bars were less than those of the Vitadur-N bars. They explained the difference as a result of retaining the 'skin layer' on the bars. This layer contains a lot of porosities that can act as stress concentrations. They also reported that fracture was initiated at the surface at the location of the porosities.

Øilo (1988) compared the flexural strength of different porcelain and ceramic materials regarding the type and amount of pores. He tested Biodent, Ceramco, NBK 1000, Vitadur-N, Vita Hi-Ceram, Cerestore, and Dicor. By contrast to the results of Kelly et al. (1989), Øilo reported the highest flexural strength in the Dicor samples. He also found the smallest pores size in the Dicor samples, which may explain the material's higher strength. It was shown that the K_{IC} values of the aluminous porcelains were 1.5 times that of the feldspathic porcelains. This confirms the reinforcing function of the strong crystalline particles on arresting crack growth. The results of this study also revealed a relationship between the number and size of the pores and fracture toughness. A greater number of defects was observed in porcelain with more particles and less glass phase. The important factors for the amount, size and form of pores were mentioned as: gas inclusion during firing, viscosity of glass phase, particle size, and distribution, and internal stresses developed during solidification.

Dickinson et al. (1989) published another study on ceramic and porcelain materials (Dicor, Cerestore, and Vitadur-N). The Cerestore crowns showed a two-phase failure pattern of crack initiation and catastrophic failure. A significant difference was found between crack-initiation load and catastrophic load in the Cerestore samples, but this difference was not significant in the Vitadur-N and Dicor samples. It was claimed by the authors that the crack was initiated and easily propagated through the Cerestore veneer. However, final failure was resisted by the high alumina core material. Although the Dicor samples appeared to be almost pore-free, they had the lowest strength values in this study. This was due to insufficient internal adaptation of the crowns to the dies, which was mentioned as another important factor in the strength of all-ceramic systems by the authors.

Regarding the importance of the role of pores and cracks in the flexural strength of all-ceramic restorations, Yen and Blackman (1993) examined the effect of etching on the mechanical properties of Dicor and Mirage. They tested different etching times (0, 0.5, 1, 2.5 and 5 minutes). The flexural strength of the samples were calculated and, as was expected, there were greater strengths for the Dicor specimens than for the Mirage specimens for all etching times. Although a 10% reduction in flexural strength for Mirage, and 7% for Dicor, samples were reported in this study after etching, the difference in flexural strength either between etched and non-etched groups, or between different etching times was not significant. The results showed that acid etching did not have a deleterious effect on the flexural strengths of the two materials. Scanning electron photomicrographs demonstrated greater surface roughness and irregularities in both Dicor and Mirage samples after etching, which did not result in a significant decrease in flexural strength. The authors claimed that the flexural strength of feldspathic porcelain and cast-glass ceramic materials may be more dependent on the internal microstructure of the material than on their surface characteristics. Another explanation for the cast-glass ceramic (Dicor) findings was that the post-cerammed surface 'skin layer' was not removed in this study. This 50 µm thick layer of $MgSiO_2$ may contribute to the material's resistance to any weakening effect of etching. By contrast, Kelly (1994) claimed that removal of the 'skin layer' increased the strength of Dicor, due to removal of flaws unique to this layer of ceramic. Kelly also mentioned other factors which influenced the strength of porcelain materials, such as surface grinding and microcracks associated with leucite grains in feldspathic porcelains. Fractographic studies of his research on all-ceramic crowns showed that failures initiated from the cementation surface, as opposed to the occlusal surface.

Yen and Blackman (1993) also believed that resin composite cement may improve the flexural strength indirectly by resisting the microleakage of moisture into surface cracks, since moisture can result in crack growth in porcelain materials. In one study by Kern et al. (1994), the influences of water storage and thermocycling on fixed bridges were examined. The material used was In-Ceram, as an alumina core ceramic veneered with Vitadur-N. Their results showed that all of the fractures were cohesive and occurred at the connectors between the retainer wings. They also indicated that water storage and thermocycling significantly reduced the fracture strength of the restorations.

To evaluate the influence of resin composite cements on the fracture resistance of all-ceramic restorations, Dietschi et al. (1990) performed a study using Vitadur-N and Ceramco II. They used both a GIC and a resin composite cement to lute the MOD inlays to the extracted teeth. Inlays cemented with resin composite resisted fracture better than did those cemented with GIC. This finding confirmed the superiority of the resin cements in static resistance to compression and flexion, as well as their better modulus of elasticity and fracture toughness. In this study, Vitadur-N with aluminium oxide profile, cemented with resin composite, exhibited the highest resistance to fracture among the restored teeth. For low-resistance samples (Ceramco II luted with GIC), fracture of the inlays with only a small amount of enamel was observed, whereas for high-resistance samples (Vitadur-N luted with resin composite) more axial fractures were found. Therefore, among the restored teeth, those with the highest resistance to fracture behaved mechanically like intact teeth, showing only axial fracture.

Since crack initiation and propagation lead to growth of internal damage and failure of porcelain materials, Peters et al. (1993) evaluated the distribution of cracks in an MOD inlay model by finite element analysis. Considering the 'crack concept', as shown by the presence of a zone of microcracks or 'crack band' in the area of highest stress, they examined crack initiation and propagation under both concentrated and distributed loads. According to the crack concept, failure starts with the growth of microcracks to macrocracks that propagate until fracture of the material occurs. The results showed the initiation of cracks at internal surfaces within the restoration, and at external surfaces near the load site. The crack initiation and propagation patterns were similar under both concentrated and distributed loads. However, the material was less prone to cracking under a distributed load because of the larger area involved.

In this study, the material degradation was explained by a softening behaviour, which means that before crack initiation, the strain-stress relationship was linear. Once a crack was initiated, the strain increased while the stress decreased. It was shown that although a ceramic material fails because of crack growth, the material has a shear resistance from the material grains. When the cracks open, the shear resistance along the cracks is reduced.

The following statements can be made from this review:

1) The flexural strength of a porcelain material can be improved by the use a rigid substructure, such as a metal or high-strength ceramic material, or by bonding the porcelain to tooth structure.

2) Dispersing a crystalline phase in the porcelain prevents the propagation of surface microcracks. Therefore, crystalline-reinforced porcelains have higher flexural strengths than do conventional porcelains.

3) There is an inverse relationship between the number and size of pores, and the flexural strength of a porcelain material.

4) Moisture and cyclic stresses reduce the flexural strength of porcelain materials.

2.1.5 Biocompatibility

Although early animal studies indicated that acid etching dentine caused moderate to severe pulp reactions, there is a high probability that the pulp irritation was mainly due to microleakage of bacteria and their products. Because acid etching increases dentine permeability and dentine wetness, successful bonding of adhesive resins to the etched dentine requires the use of hydrophilic resins which bond equally to both peritubular and intertubular dentine (Pashley 1992). Unlike enamel, when dentine is etched its surface becomes mineral-poor and protein rich, and it tends to become wetter. The purposes of etching dentine are; removing the smear layer to permit bonding to the underlying dentine matrix, demineralising the superficial dentine to permit resin infiltration into the surface, uncovering both intertubular and peritubular dentine, and cleaning the dentine surface free of any bioforms (Pashley 1992). Pashley also stated that the collagen phase of the smear layer is acid insoluble, and responsible for reduction of dentine permeability. If sufficient etching time is allowed, then all of the smear layer and smear tags will be removed. While this permits the penetration of resin into the tubules, it also permits the outward flow of the dentinal fluid which may interfere with the bonding of the adhesive resin.

Related to the pulp response, most authors believe that many pulpal reactions are due to bacteria and their products rather than to the effect of acid per se. The role of acid is to increase the dentine permeability. Therefore, providing a good permanent seal by a restorative material is obsolutely necessary. Various acids and agents are capable of removing the smear layer. Stanley et al. (1988) evaluated the pulpal response to different treatment materials after seven and 21 days. The results showed that regardless of the treatment materials, pulp response was minimal in the 7-day specimens. The authors stated that this result was in accord with the removal of the smear layer and formation of a microporous and rigid structure impregnated by NTG-GMA (N ρ-tolyl glycine glycinemethacrylate), or NPG (N-phenylglycine) and PMDM (pyromellitic dianhydride 2-hydroxyethyl methacrylate). The PMDM was polymerised and copolymerised with the resin of the composite, thereby sealing the tubules from oral contaminations. No bacterial invasion due to microleakage was reported in the treatment groups. The pulp reaction for the 21-day specimens was half of that of the 7-day specimens.

White et al. (1992a) compared the pulpal responses to dentine etching and dentine treatment with two dentine primers, to an eugenol-containing cement and an acidic cement. Acidic cement presented the most severe pulp reaction, while dentine etching and treatment with the primers were not harmful for pulp healing. Other studies of pulpal responses have found similar results (White et al. 1992b, Snuggs et al. 1992).

It can be concluded that etching dentine per se does not irritate the pulp, but bacterial microleakage around the restoration will cause adverse pulpal reactions. Regarding the concentration of currently used acids, Pashley (1992) recommended the application of acids which were isotonic with body fluids (approximately 1%), and to use a limited etching time required to produce an optimum bond.

The cause of post-operative sensitivity can be summarised as:

1) Inadvertent etching of dentine without adequate sealing,

2) Desiccation of exposed dentine,

3) Separation of resin composite from cavity wall as a result of polymerisation shrinkage,

4) Bacterial colonisation from marginal leakage.

2.1.6 Clinical Behaviour

Although etched-porcelain resin-bonded restorations have been used for many years, there are few long-term controlled clinical evaluations available. As reviewed by Etemadi (1994), many authors have examined in vitro aspects of these restorations and tried to relate the results to the clinical behaviour of the restorations. However, strong correlations between in vitro testing and in vivo performance are lacking.

As with any other restorative systems, the resin-bonded porcelain restorations have been evaluated from different aspects; such as marginal adaptation, marginal staining, restoration fracture, wear of the restorative material itself or of the opposing tooth structure, postoperative sensitivity, and recurrent caries.

Jensen (1988) evaluated 310 resin-bonded porcelain inlay and onlay restorations in a two-year clinical trial. The restorations were examined at baseline, one and two years using USPHS (United States Public Health Service) guidelines. No colour mismatch, marginal discolouration, secondary caries, wear or fractures were seen at baseline. However, the percentages of restorations which received Alpha ratings decreased over time. Only one restoration had some radiolucency at a proximal margin after two years, which was replaced. For marginal adaptation, 94.8% of the restorations seen at one year and 90.4% of those seen at two years were rated Alpha, while 5.2% and 9.6% of the restorations seen at one year and two years, respectively, were rated Bravo.

Krejci et al. (1992) evaluated a pressed-glass ceramic material (IPS/Empress) clinically over 1.5 years. Ten patients received one inlay in a premolar. All cavity margins were located in enamel. Two replicas of each restoration were taken at the insertion appointment and after 1.5 years for SEM observations of marginal adaptation. No bulk fracture, surface porosities, wear or recurrent caries were detected clinically. Occlusal marginal discolouration was low, but some slight marginal discolouration was observed proximally. Marginal adaptation was excellent at baseline, with openings only detected along 2.6% of tooth/cement, and 1.8% of the cement/inlay interfaces. After 1.5 years a significant disintegration of cement/inlay interfaces had occurred, and the amount of gap-free margins at this interface dropped from 97.4% to 66.8%. The authors attributed this problem to the transferring of occlusal forces to the margins and/or microfilled resin cement or base material, which do not support the restoration as well as dentine does. SEM examinations showed an increase of underfilled margins from 10.8% to 35.5% during the study. Only one patient had a slight hypersensitivity to occlusal loading and temperature changes, which disappeared after one month.

A two-year clinical study by Broome et al. (1994) evaluated two ceramic inlay systems: Dicor cast-glass ceramic cemented with Dicor LA cement, and Mirage porcelain cemented with Mirage FLC. Twenty eight Class II inlays were placed in maxillary premolars and evaluated at one month, six months, one year, and two years. The restorations were examined clinically and radiographically for marginal adaptation, marginal staining, and secondary caries. After two years, one Dicor restoration exhibited bulk fracture. No marginal staining or secondary caries was noted. The marginal gap width (measured by SEM) was 177.6 μm for Mirage and 144.5μm for Dicor inlays, which was significantly less for Dicor than for Mirage. SEM replicas revealed wear of resin cement for both groups, with the greatest rate occurring in the first six months. Fracture of the ceramic margins occurred in 9% of Mirage and 12% of Dicor inlays after two years. This is a function of wear of the resin cement which led to exposure of the ceramic margins. Therefore, the results indicated that the marginal degradation of ceramic inlays consisted of both cement wear and chipping of the ceramic.

Ferrari (1991) compared the microleakage and marginal discrepancies of 14 Dicor crowns with two gold onlays and one metal-ceramic (PFM) restoration. The preparations for Dicor crowns were made with a shoulder finish line, and for gold onlays and the PFM crown were made with a shoulder bevel finish line. The gold and PFM restorations were cemented with zinc phosphate (ZP), and the Dicor crowns were luted with ZP, GIC and resin composite cements. The Dicor crowns which were luted with resin composite cement had been treated in three ways: 1) internally etched, silanised, dentine treated with Gluma bonding system, 2) no etch, no silane treatment, dentine treated with Gluma, 3) etched and silanised without dentine treatment. The teeth were extracted after 4-7 months and stained with methylene blue. They were then sectioned buccolingually and observed under the SEM and stereomicroscope. Gold onlays and the PFM crown had lower microleakage than the Dicor crowns. Dye penetration was the deepest in the Dicor group cemented with GIC. Dye penetration in Dicor crowns subgroup 1 was lower than in the two other groups. The ZP cement thickness was maximum in Dicor crowns and minimum in gold onlays. The GIC cement was not sufficient to avoid microleakage. The marginal adaptation of bevelled restorations was better than for the Dicor crowns.

In a clinical study by O'Neal et al. (1993), four different types of inlay systems were evaluated. Two hundred and thirty inlays/onlays placed for a series of patients consisted of: 1) direct resin composite (Brilliant), 2) indirect chairside die (P-50), 3) indirect laboratory processed ceramic (Cerinate), and 4) CAD/CAM (Cerec). An impression of each inserted restoration was taken at baseline, six months, the end of the first year, and second year. The width and depth of interfacial defects were then measured. The least interfacial gap was observed in the Brilliant restorations, and the widest gap was observed in the Cerinate restorations. Vertical loss (wear) of luting agents was minimum in the Brilliant inlays/onlays, and maximum in the Cerinate restorations. A direct relationship between the interfacial gap and the vertical loss of the cement was found in this study. Therefore, the greater the gap width, the greater the wear of the cement. The depth/width ratio increased during the first year and then tended to level out. The depth/width ratio was greater for the hybrid cement when compared to the submicron-filled resin cement.

An important factor in the clinical success of all-ceramic restorations is successful bonding of the restoration to tooth structure. This aspect was studied by Malament and Grossman (1992). They compared the success of resin-bonded Dicor crowns to those luted with ZP and GIC cements. Some 985 crowns were placed in a series of posterior and anterior teeth. The results showed 18 failures from 616 bonded crowns with ages up to four years, and 50 failures from 369 non-bonded crowns with ages up to seven years. A decrease in the failure rate of non-bonded crowns was observed at 3.5 years. Fracture rates for molar crowns were significantly higher than for anterior or premolar crowns when GIC or ZP cements was employed. In contrast, a low fracture rate (2.9%) for resin-bonded crowns was uniform, irrespective of tooth location.

Höglund et al. (1992) evaluated 118 Class II feldspathic porcelain (Mirage) inlays/onlays inserted in patients' teeth. Half of the restorations were cemented with a dual-cured resin composite (Mirage) and the other half were cemented with a GIC (Fuji I) cement. After two years, only one inlay (2%) in the resin composite group fractured, while in the GIC group nine inlays (15%) fractured. Most failures were adhesive. Both cements showed good adhesion to tooth, but differed in adhesion to the porcelain. The low degree of marginal discolouration and the absence of recurrent caries indicated a good seal of the margins in both groups.

In a clinical trail, Ellison et al. (1992a) examined the survival of cast-glass ceramic (Dicor) crowns placed in 20 first molars. This study was planned in response to an earlier trial in which a high proportion of molar glass-ceramic crowns fractured before two years of clinical use. A greater tooth reduction (1.0 mm shoulder margins, and 1.7 mm occlusal reduction) was made when compared to the first study. The crowns were luted with zinc phosphate cement. The patients all had anterior occlusal guidance. After four years, two (10%) had failed, 14 (70%) were clinically acceptable, and four (20%) were lost to follow up. The first failure was from a fracture subsequent to endodontic access (2.7 years), and the second was from caries along the margins (3.0 years). In comparison to the previous trial which showed seven of 13 (54%) functional fractures, this study had no functional fractures. The results indicated that first molar glass-ceramic crowns can resist fracture when adequate tooth reduction is undertaken in selected patients. The same authors (1992b) also placed 80 Dicor crowns in 59 patients to investigate the clinical performance of cast-glass ceramic material. The criteria for rejection of preparations from the study were: undefined margins, shoulder< 0.5 mm, axial reduction< 1.0 mm, and occlusal reduction< 1.3 mm. The crowns were luted with the same cement. From the 80 crowns, 32 (40%) had failed, 25 (31%) were clinically acceptable, and 23 (29%) were lost to follow up. The most common reason for failure was fracture through the body of the crowns. Other failures were: open margins, caries, and fracture of supporting structure (tooth or build-up). The highest failures were for molars, and the lowest for anteriors. Therefore, the results showed a high failure rate for Dicor crowns because the patients were not specially selected, or tooth reduction was not adequate.

Noack and Roulet (1994) evaluated 210 Dicor inlays after four years of clinical service. The quality of the restorations was assessed clinically using modified USPHS Ryge-criteria. The mode of failure was assessed photographically. Within four years, 28 (13%) inlays had failed. Sixteen failures were cohesive through the inlays or from cusp fracture, while fractures as a result of the restorative process were observed in 12 cases. Reasons for failures were: insufficient enamel in cervical boxes, endodontically treated teeth, and wide cavities. Ninety one percent of the characteristics of the inlays were recorded as Alpha, of which 81% showed minor marginal wear of the luting composite. This investigation concluded that the reinforcement of restored teeth by the adhesive technique must be questioned.

The lifetime of three types of resin-bonded porcelain restorations was estimated by Scherrer et al. (1995). The materials were Cerestore (N= 30), Dicor (N=30), and Hi-Ceram (N=22). The maximum predicted characteristic lifetime (at which 63% of the restorations had failed) of the restorations was 23 years for Cerestore, 35 years for Dicor, and 30 years for Hi-Ceram. These estimates appeared somewhat optimistic.

Seventy five Empress resin-bonded porcelain crowns cemented with Dual and Variolink resin cements were clinically evaluated by Sorensen et al. (1995) within 30 months. The preparations had 1.3 mm of axial and 1.5 mm of occlusal reduction. The short-term results showed no fracture, or any other failures. Only two of 33 patients reported postoperative sensitivity, which lasted one to two months.

A four -year clinical trial of 101 posterior Dicor crowns with 1.5 mm of axial, and at least 2.0 mm of occlusal reduction was carried out by Cavel et al. (1995). There were 14.4% of restorations which fractured. No marginal discolouration, colour mismatch, secondary caries, loss of marginal adaptation and proximal contacts were recorded after four years.

Friedl et al. (1995) examined the margins of 50 Mirage inlays in vivo over two years. All margins were located in enamel, and they were evaluated clinically, and quantitatively using SEM. After two years, the restorations showed no colour change, no marginal discolouration, and no secondary caries. Postoperative sensitivity was found in two restorations, which disappeared after two weeks. The quantitative marginal examination showed less marginal gap at the enamel/composite interface than at the composite/ceramic interface. The gap at both interfaces increased significantly during the first year, whereas the percentage of gap at the composite/ceramic interfaces did not increase during the second year. This study showed a good clinical performance for a feldspathic porcelain (Mirage) after two years.

The longevity of 123 Class I and II Dicor inlays (46 premolars and 74 molars) cemented with Duo Cement, Dual Cement, and Sonocem was clinically evaluated over 4 to 82 months by Roulet (1995). Twelve inlays (9.7%) failed because of fracture or endodontic problems, and one was replaced because of postoperative sensitivity. The estimated longevity of the inlays was 76% after six years with no difference between the luting cements. Premolar teeth had a better success, which was not significant. Wear of resin composite cement was observed in randomly-selected inlays, by SEM assessment.

In one clinical study, 97 IPS/Empress inlays (73 Class II) and onlays (24 Class II) were examined after twelve months by Reinelt et al. (1995). Only one restoration fractured. All other clinical features such as colour, marginal adaptation, contacts, and tooth and restoration integrity were highly satisfactory. Hypersensitivity was observed after six months (10%) and twelve months (13%) without any clinical consequences.

Isidor and Brϕndum (1995) performed a clinical study to evaluate the survival rate of 25 Mirage inlays (13 premolars and 12 molars). The inlays were cemented with a light-cure composite cement (Mirage Porcelain System) and a dual-cure cement (Mirage FLC Porcelain System). A light-cure GIC liner was placed in the deep areas of the cavities. The results showed 12 failures which led to replacement of the restorations. Ten failures were due to fracture, one was from recurrent caries, and one was from a marginal gap at a proximal area. All fractured inlays had less than 1.5 to 2.0 mm thickness. Inlays cemented with the light-cure resin composite cement exhibited significantly more failures. The average clinical service before failure was 15.7 months, and the inlays placed in molars had more tendency for failure than those in premolars.

A three-year clinical study by Qualtrough and Wilson (1996) of 50 Mirage inlays (21 Class I, 29 Class II) found that five failed within one month of placement and another three failed by six months, usually from bulk fracture of the porcelain. There was approximately 1.5 - 2.0 mm occlusal thickness of porcelain present, and a dual-cure luting cement was used, but no dentine bonding system.

Mörmann and Krejci (1991,1992) evaluated eight MOD Cerec inlays fabricated from Vita Cerec MK I blocks and placed in lower first molars after five years of clinical service. The inlays were luted with a microfilled or a hybrid resin cement. All of the restorations rated Alpha for wear, recurrent caries and colour match. Five USPHS Alpha and three Bravo ratings were obtained for marginal discolouration and marginal integrity, respectively. From SEM examination, 81±13.3% of occlusal margins of tooth/cement, and 84.1±14.4% of occlusal margins of cement/inlay interfaces rated as continuous. In the axial portion 73.6±19.7% of margins of tooth/cement interfaces, and 87±11.5% of the cement/inlay interfaces were continuous. Two restorations were fractured. This small, long-term clinical study showed a good clinical performance of the Cerec inlays. However, based on the SEM findings, improvements to the ceramic material and its properties, the cavosurface design and the resin composite cement are suggested.

In another study, Mörmann et al. (1991) evaluated 94 two-surface and three-surface Cerec restorations inserted in premolars and molars after three years. The preparations were parallel without enamel bevels (except for the gingival and lateral proximal margins). The restorations were also evaluated using the USPHS criteria. Alpha ratings were obtained in 63% of restorations for margins, 97% for contour, 76% for surface texture, and 63% for colour match. Hypersensitivity to cold was reported in seven patients (seven teeth). The discomfort persisted from one month to 12 months.

In a comparison of Cerec inlays with laboratory-fabricated inlays, Thordrup et al. (1991) evaluated MOD direct inlays (Cerec Vita Blocks) and indirect laboratory inlays (Vita Hi-Ceram) in vivo and in vitro. Ten direct and 10 indirect restorations were made on extracted molar teeth and were then thermocycled (2500 times). Marginal gap, cement thickness and dye penetration were measured microscopically from 75-100 μm thick sections. Twenty molars were selected for the clinical evaluation of direct and indirect inlays. The restorations were evaluated clinically after one week. Marginal fit of indirect inlays was superior to that of the Cerec restorations for both in vivo and in vitro evaluations, specially after cementation. An excess of resin cement was observed with both methods of fabrication. In the clinical study, all indirect inlays received the rating R for morphology and colour match, while six Cerec inlays rated S for colour match and morphology. The frequency of hypersensitivity after cementation was similar for both groups (direct and indirect). Short hair-line cracks were seen in one in vitro and in two in vivo indirect inlays, whereas no cracks were observed in the Cerec restorations.

One hundred and eighteen Class I and II inlays/onlays restorations, fabricated from Dicor or Vita ceramic, were placed (by means of the Cerec system) in a series of patients by Isenberg et al. (1991). Each restoration was evaluated directly (based on the USPHS system), and indirectly (using replicas before and after cementation) at baseline, six months, one and two years. Colour matching for both materials was not rated below 98% Alpha over the two years of the study. No marginal staining and secondary caries were observed over two years with any of the materials. Only three of the 118 restorations fractured across the isthmus region during two years of clinical service.

Indirect evaluations showed that a higher rate of horizontal and vertical loss of resin cement occurred in the first year, but the losses then became constant.

Calamia (1989) evaluated 115 porcelain laminate veneers fabricated from Mirage porcelain and cemented with Comspan in a clinical trail of three years. The veneers were cemented on either prepared (N=72) or unprepared (N=43) teeth. The results showed no colour change after three years. However, marginal discolouration was observed in 18.6% and 15% of unprepared and prepared teeth, respectively. Marginal adaptation deteriorated after three years in both groups. Only three fractures (4.1%) were found for veneers in prepared teeth. One of them was in combination with debonding of the veneer.

Rucker et al. (1990) evaluated 44 porcelain and 44 resin veneers after two years. Out of 37 porcelain and 36 resin veneers available at two years, nine resin veneers failed while none of the porcelain veneers failed.

Shaini et al. (1995) evaluated the clinical performance of 372 porcelain laminate veneers cemented with a microfilled resin composite. Survival analysis showed 88.5% success after one year, which decreased to 48% after six years. The major failures were fracture (54%) followed by debonding (21%). The majority of the failures occurred in those veneers cemented over existing restorations.

Since most single all-ceramic restorations have been shown to be acceptable, some investigators have focused on all-ceramic fixed prostheses. A study by Christensen and Christensen (1992) examined 20 anterior and 20 posterior three-unit ceramic prostheses of varying designs including full crown, inlay, and veneer abutments, and cantilever pontics. The preparations involved 1-2 mm tooth reduction and heavy chamfer margins, with acid etch and/or dentine adhesive being used. The results at two years showed

64% fractures (81% posterior and 47% anterior), wear on 80% of the opposing teeth, and 10% irreversible pulpitis which needed endodontics. No debonding, no caries, no change in colour match and margin staining were observed. The results showed that 80% of anterior prostheses could serve adequately for two years at least, if full abutment crowns were used. Posterior prostheses of all the designs tested, plus anterior prostheses using inlay and veneer abutments, or cantilever pontics, were contraindicated.

This review of clinical behaviour of resin-bonded porcelain restorations highlighted the following outcomes:

1) Fracture of restorations is a very common failure mode reported in most of the studies mentioned, although less with machine-milled ceramics.

2) Postoperative sensitivity is another problem commonly reported by investigators.

3) Recurrent caries is not routinely reported in clinical trials of these restorations.

4) Wear of resin composite cement occurs, and marginal discolouration may also occur, in all types of resin-bonded porcelain restorations. In some cases wear leads to exposure of ceramic margins. Therefore, both restoration and enamel chipping at the restoration margins can occur. Wear of cement happens at a higher rate for the first six to twelve months of clinical service, after which it becomes constant. For this reason, marginal deterioration is a common problem for resin-bonded porcelain restorations.

5) Glass ionomer cements are not successful for providing gap-free margins and reduced fractures. The best material which bonds to both ceramic and tooth structure is resin composite cement.

CHAPTER THREE

Research Objectives

3.1 Research Objectives

From a review of the literature, it can be seen that the clinical evaluations were generally limited by time or sample size. The sample sizes were usually small or, if large enough, then the duration of study was short. In most of the clinical trials, the investigators focused on one type of resin-bonded porcelain restoration without making comparisons between the different restoration types (eg inlay/onlay, onlay/shell crown, fixed-fixed/cantilever bridge). Again, most of the clinical trials were carried out under ideal conditions, which may differ from the uncontrolled but more realistic conditions of private practices. Therefore, the aim of this study was to undertake a long-term retrospective evaluation of resin-bonded porcelain restorations of different types placed in a private practice, to determine :

1) the preparation designs and dimensions, which might be different from those reported previously in the literature. It is hypothesised that different preparation designs for each type of restoration may affect the longevity of the resin-bonded porcelain restorations,

2) modes of failures for these restorations including fractures, debonding, irreversible post-operative sensitivity, colour mismatch,

3) the survival rates of restorations according to the types of restorations (single, bridgework, with and without metal reinforcement). It is hypothesised that different

types of restorations may have different clinical performances. The different restoration sites (posterior, anterior), different oral habits (bruxing), different age groups and gender, bases and luting cement types, and operators may also affect the survival rates of the resin-bonded porcelain restorations.

For this study, 536 restorations of different types were selected from a specialist private practice. From these restorations, 105 were selected for assessment of restoration designs and dimensions. Data for restoration characteristics and longevity were obtained from the patients' casenotes.

CHAPTER FOUR

Methods and Materials

4.1 Introduction

The present study is a clinical evaluation in three parts of resin-bonded porcelain restorations. In the first section, selected measurements were taken from stone dies of prepared teeth to find common elements of cavity design for the resin-bonded porcelain onlay and shell crown (porcelain laminate crown) restorations. In the second and third sections, patients' casenotes were examined to find information on the failure modes, and the longevity of resin-bonded porcelain restorations constructed and inserted in a private practice. Definitions of the restorations are described at this section to clarify the terms used in this research report.

4.2 Definition of restorations

The following definitions are based, where possible, on those defined by Jablonski (1992), Zwemer (1993), and by the Glossary of Prosthodontic Terms (1994).

Inlay: an indirect restoration of metal, porcelain or resin made to fit an intracoronal tapered cavity preparation into which it is luted.

Onlay: a cast metal, porcelain or resin composite restoration retained by frictional or mechanical cavity preparation factors and which overlays one or more tooth cusps.

Laminate or veneer: a conservative, aesthetic restoration of anterior teeth, bonded to the tooth. (Tooth-coloured materials may also be fused, cemented or bonded to metal crowns and pontics).

Crown: an artificial prosthesis replacing the natural tooth crown surfaces partly (partial veneer) or completely (complete or full veneer).

Many types of artificial crowns have been described, none of which adequately describes the concept of resin-bonded porcelain coverage of tooth surfaces. Inadequate terminology includes a) shoulderless jacket crown, and b) shell or cap crown (preformed thin metal crown filled with a large amount of cement). Perhaps, these resin-bonded restorations should be called either porcelain veneer crowns (not to be confused with porcelain veneered crowns), or porcelain laminate crowns. In this manuscript, however, they are called porcelain shell crowns.

It is often difficult to classify tooth preparations for resin-bonded porcelain restorations, because such restorations do not require conventional cavity or tooth preparation designs for adequate retention and resistance form, and the preparation are usually made to conserve as much natural tooth substance as possible. For instance, no dictionary of dental terminology describes a chip veneer, which is a small piece or sliver of resin-bonded restorative material used to replace missing tooth substance or to modify existing tooth contours.

Because of the more flexible preparation designs possible, one type of resin-bonded restoration tends to blend in with another type, so that when the conventional distinctions are applied to laminate veneers, laminate crowns, onlays and inlays, these often become blurred. This leads to confusion between dentists and third-party insurance providers. Unfortunately, suitable terminology and description is also lacking in even recent dental dictionaries.

4.3 Sample Selection

The present study involved 536 resin-bonded Mirage (Appendix I) porcelain restorations of different types placed in 222 patients. The restorations were selected from a specialist private practice in which two prosthodontists worked. The patients' case notes were withdrawn alphabetically from storage until sufficient number of restorations were collected, which comprised almost all of the resin-bonded restorations placed up to the end of 1993. From the patients' case notes, it appeared that the practitioners began construction of these restorations in 1988. To provide a reasonably long-term clinical evaluation time, attempts were made to collect the most recent information about the restorations. Therefore, all data were updated in July 1995. However, not all patients were available for follow up, since some of them had changed either their practitioners or addresses, or failed to attend for the follow up sessions. The data for these patients were therefore considered as being 'censored' for statistical analysis.

Permission for the study was obtained from The University of Adelaide Committee on the Ethics of Human Experimentation.

4.4 Part One: Restoration Designs and Dimensions

From 536 restorations, the stone dies of 105 posterior single restorations (inlay, onlay, shell crown) were selected haphazardly for this part of the study. The aims of this section were to find: 1) common preparation designs and dimensions for the resin-bonded porcelain restorations placed in a private practice and to compare them to those designs reported in the literature, and 2) the relationship between preparation dimension and restoration fracture. For these purposes, a proforma (Form 1, Appendix II) was used. This form consisted of:

4.4.1 Patient Details

This section was designed to give some general information about each patient such as the registration number, surname and initial, birthdate, and the box number in which the patient's stone casts and dies were kept. These details were not used in the report.

4.4.2 Restoration Details

This section consisted of the restoration registration number, tooth number (FDI), surfaces involved in the preparation (occlusal, mesial, distal, buccal or lingual), restoration type (coded as 2= Shell Crown, 3= Inlay, 4= Onlay), and dates of placement (and replacement if there was any failed restoration).

4.4.3 Measurements

Data were obtained from measurements taken at the mesial and distal aspects of stone dies of posterior teeth. In this part of the study, anterior tooth restorations were excluded. When taking the measurements, the dies were first inserted into a Mirage full arch die-locator tray (Appendix I), and the opposing full arch stone cast was then occluded to check the occlusal contact relations. The measurements were taken using a dial calliperwith 0.1 mm calibration (Appendix I). The measurements were:

4.4.3.1 Intercuspal Width

This was measured at the mesial and distal cusp sites for molars ("a" in Form 1), and intercuspally for premolars. For this purpose, the highest points of the buccal and lingual cusp preparations were considered as representing the sites of the cusp tips. If the reduced cusp was flat, then the centre of the reduced surface was selected as the reference point. The intercuspal width was then measured as the distance between these two points (Figures 1 and 2).

4.4.3.2 Isthmus Width

Isthmus width measurement is shown as "b" in Form 1. The narrowest part of the cavity at the occlusal surface was selected, and the isthmus width was measured at the occlusal cavity margins (Figure 3).

4.4.3.3 Proximal Width

Proximal width is shown as "c" in Form 1. In each cavity with a proximal box, the cavosurface margins were pencilled, and the proximal width was measured at the widest part (Figure 4).

4.4.3.4 Height of axial wall

Height of axial wall is indicated as "d" in Form 1. The measurement was taken as the distance between the gingival floor and pulpal floor (Figure 4).

4.4.3.5 Depth of Occlusal Floor from the Central Fissure

Depth of occlusal floor from the central fissure was not possible to measure directly. Therefore, a silicone impression of the die was taken (Appendix I). For this purpose, a small amount of a laboratory putty was mixed with its accelerator and applied to the die which had been inserted into the Mirage tray. The opposing cast was immediately occluded and retained in position until the putty was set. The impression was then cut buccolingually at the mesial and distal cusp sites for molars, and intercuspally for premolars, to take more accurate measurements (Figures 5 to 8).

The depth of occlusal floor from the central fissure is indicated as "e" in Form 1, and was measured at the depression between buccal and lingual cusps (Fig. 9).

4.4.3.6 Cusp Reduction

Cusp reduction is indicated as "f and g" in Form 1 and measurements were taken of the buccal cusps of the lower, and of the palatal cusps of the upper posterior teeth (working cusps, Figure 10). The non-working cups of these teeth were not measured because of the false thickness of impression material in these areas (more than 3-4 mm).

4.4.4 Preparation Characteristics:

These characteristics were assessed on the dies using a magnifier (1.5 x magnif.) to find any specific design features of the restorations as follows:

4.4.4.1 Gingival margins of restorations terminating in dentine or enamel,

4.4.4.2 Margins bevelled occlusally or gingivally,

4.4.4.3 Opposing tooth contacts on margins,

4.4.4.4 Angular cavosurface margin outlines,

Figure 1- A representative photograph of a prepared molar tooth showing the cusp tips (arrows) from which the intercuspal widths were measured.

Figure 2 - A representative photograph of a prepared premolar tooth showing the cusp tips (arrows) from which the intercuspal width was measured.

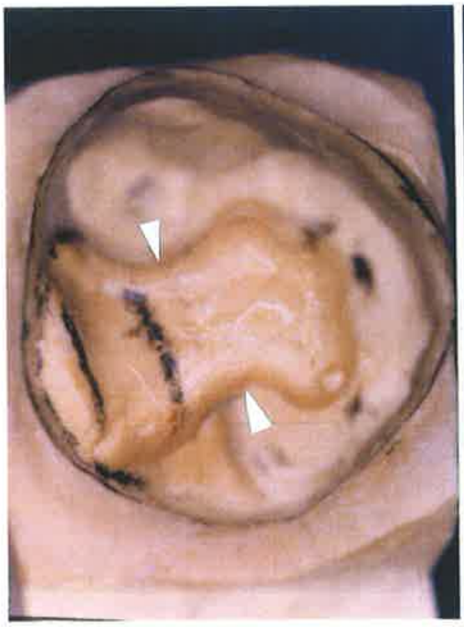


Figure 3 - A photograph of a prepared molar tooth showing the points (arrows) at which isthmus width was measured at the narrowest site.

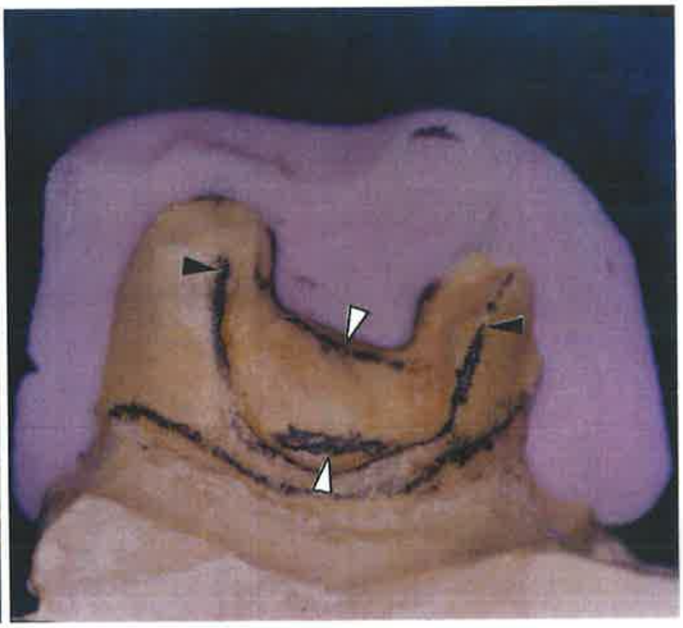


Figure 4 - A photograph of a molar tooth (46) representing proximal width measured at widest area (black arrows), and height of axial wall measured between gingival floor and pulpal floor (white arrows).

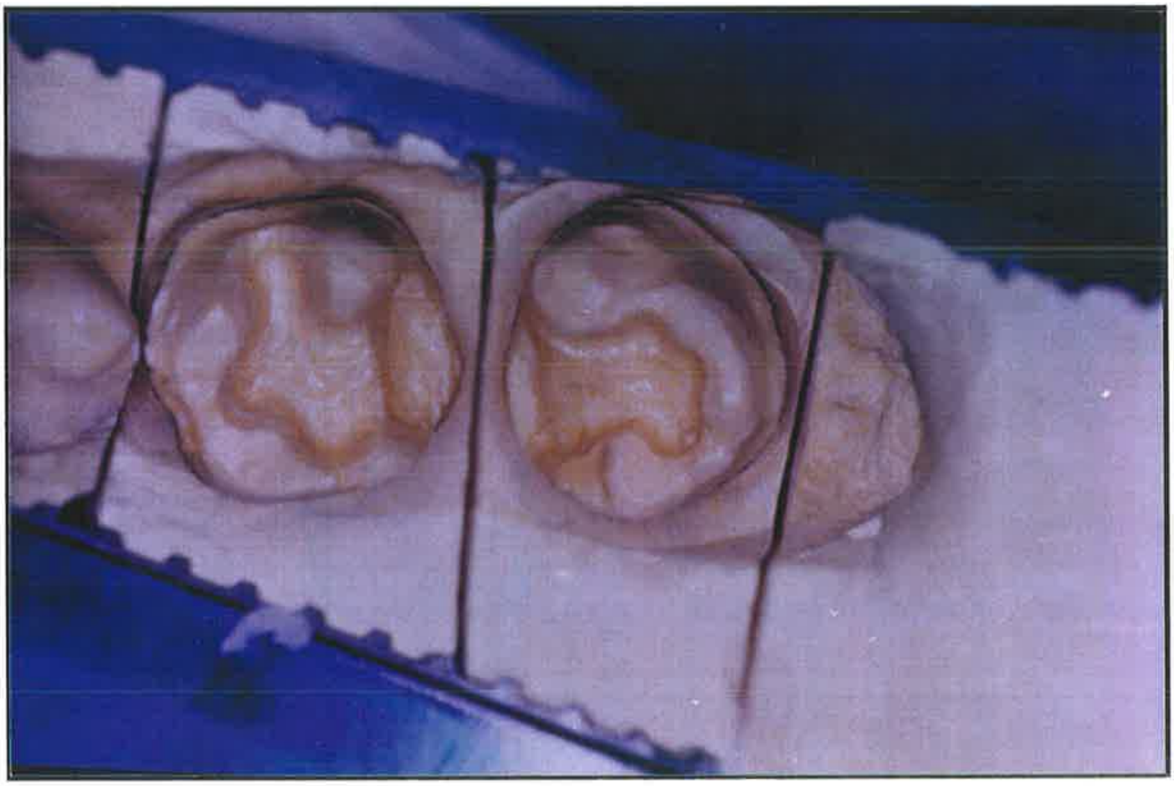


Figure 5 - An occlusal view of two dies inserted in a Mirage tray with shell crown preparations on molar teeth (46 and 47).

Figure 6 - The same dies in Figure 5 with a putty impression and occluded with the opposing cast.

Figure 7- An occlusal view of the same impression in Figure 6 after the putty has set.

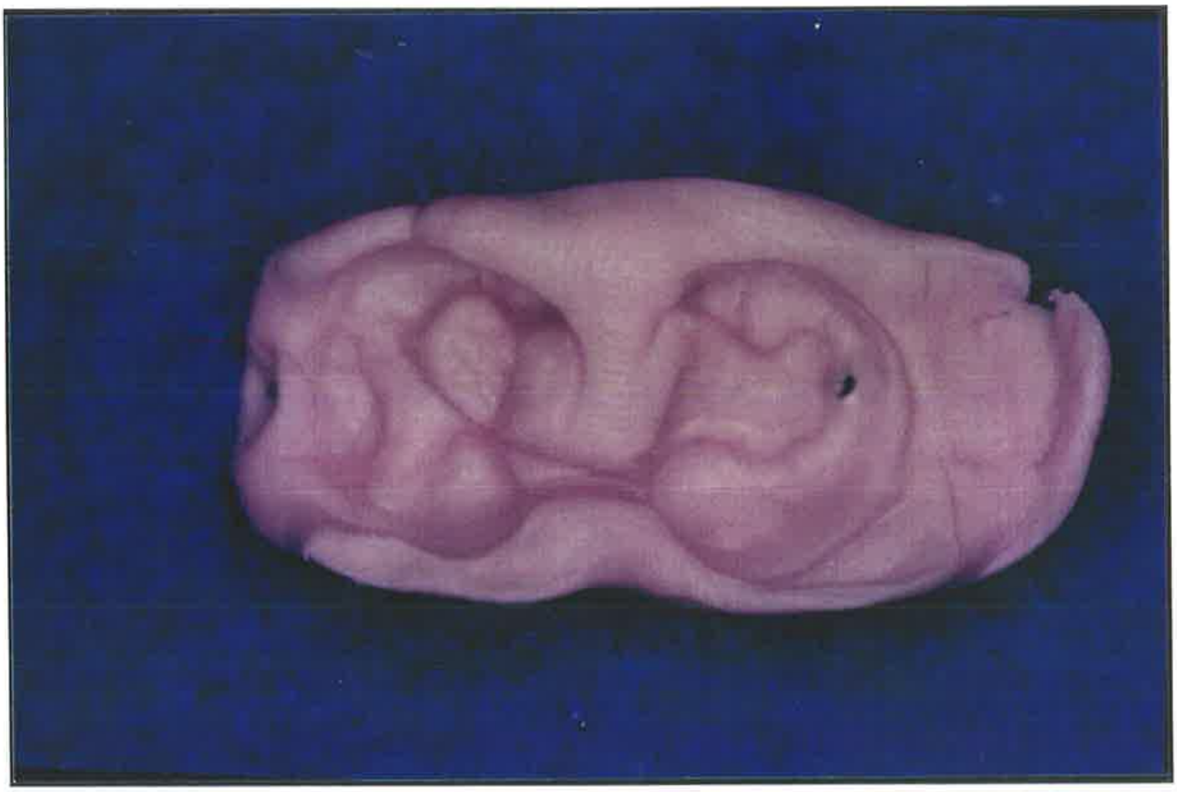


Figure 8 - The internal view of the same impression in Figure 7.

Figure 9 - A photograph showing the distal view of tooth 46 in Figure 5 with sectioned impression. Depth of occlusal floor was measured from the depression between buccal and lingual cusps (white arrow) and pulpal floor (black arrow).

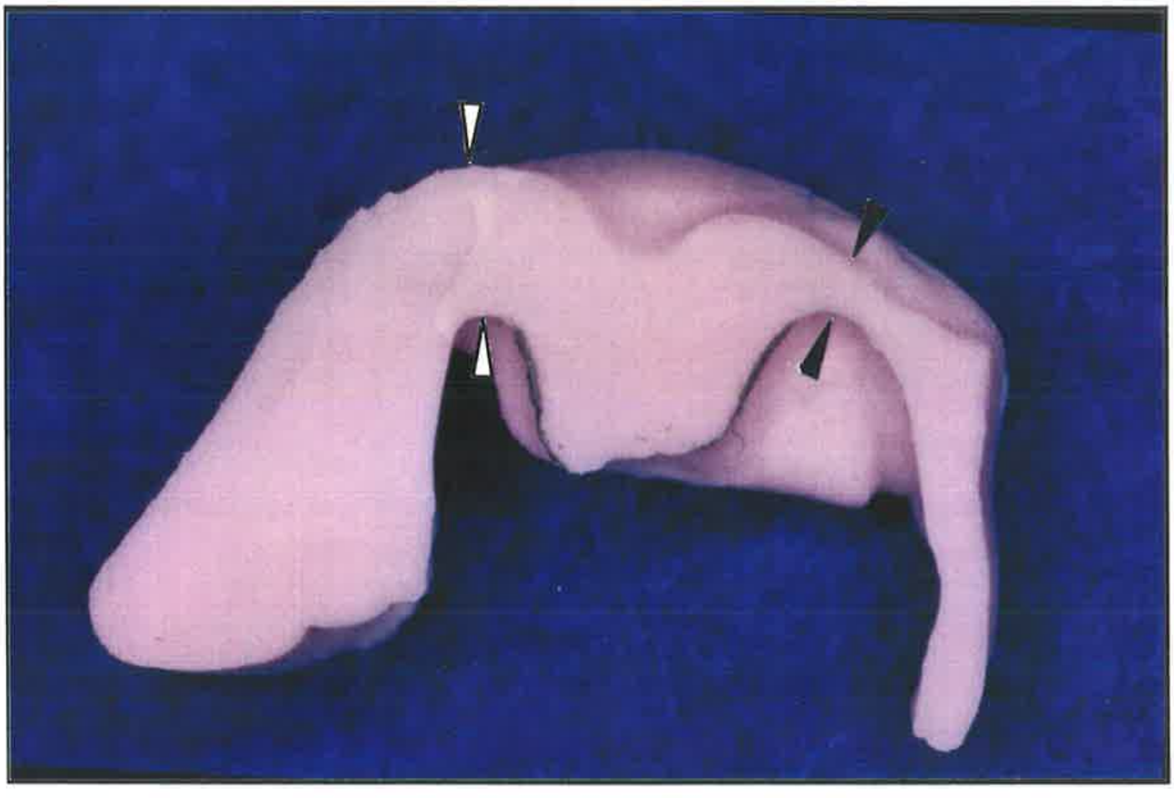


Figure 10 - The same sectioned impression of the tooth in Figure 9 used for cusp reduction measurement at buccal cusp (black arrows). Non-working cusps show a false thickness (white arrows). The preparation taper was measured as an angle between extensions of the pencilled lines.

4.4.4.5 Sharp internal line or point angles,

4.4.4.6 Retention grooves present,

4.4.4.7 Preparation taper: Preparation tapers of restorations without occlusal and proximal boxes were measured directly on the dies. For this purpose, the extensions of the buccal and lingual walls of the preparations were copied onto a piece of paper. The angle between the two lines was then measured with a protractor (Fig. 11, page 60).

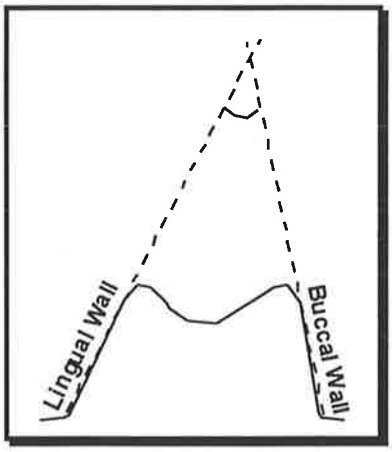


Figure 11: Preparation taper measured in a premolar or a molar tooth without occlusal or proximal boxes.

Preparation tapers of restorations with occlusal and proximal boxes were measured indirectly from impressions of the internal walls (Figures 9 and 10 pencilled area). Again, the extensions of the internal buccal and lingual walls were copied onto a piece of paper. The angle between the two lines was measured, as before, with a protractor.

4.4.4.8 Metal reinforcement present: A metal substructure was sometimes fabricated to reinforce the restorations. In this study, the presence of metal substructures in restorations was assessed using information from the patients' casenotes. Figures 12 and 13 show an example of an onlay restoration with metal reinforcement.

Finally, for further evaluation of different preparation designs, a colour transparency was taken at 1:1 magnification of each die, using a Minolta camera (Appendix I).

The same measurement procedures were undertaken for any replaced restorations, to find out if there were any changes made to the original cavity dimensions and designs.

The dies of thirty restorations were selected haphazardly from the same 105 stone dies, and all measurements and assessments were duplicated to evaluate examiner reliability.

Figure 12 - A metal-reinforced onlay restoration on tooth 46.

Figure 13 - The fitting surface of the same restoration in Figure 12.

4.5 Part Two: Restoration Failures and Survivals

Further clinical information was obtained in the second section of the study. For this part, another proforma (Form 2, Appendix II) was used on which data were again entered from the patients' casenotes. The aims of this section were : 1) to find the most important reasons for the placement and replacement of the resin-bonded restorations, 2) their modes of failure and possible failure reasons, 3) the treatment given after any restorations had failed, and 4) the longevity or survival rates of the restorations.

Five hundred and thirty six different resin-bonded porcelain restorations were examined. The types of restorations differed from single (veneer, incisal veneer, chip porcelain, shell crown, inlay, onlay,) to various bridgework (fixed-fixed, or cantilever).

To minimise the number of different factors affecting the longevity of the resin-bonded porcelain restorations, only those fabricated from Mirage porcelain material were evaluated. Although a single porcelain material was used, different resin luting cements had been chosen by the two operators (Appendix I). The data obtained from Form 2 included:

4.5.1 Baseline Data

Baseline data included registration number, patients' surnames and initials, patients' gender, and birthdate

4.5.2 General Oral Features

These might be considered as associated risk factors, such as bruxism/attrition (obvious wear present on posterior teeth as assessed from casts and from comments of the operators).

4.5.3 Restoration Information

a. Tooth number (FDI) for which the restoration was fabricated.

b. Restoration type coded as follows:

1. veneer,

2. shell crown,

3. inlay. (Subsequently excluded, as only two inlays),

4. onlay,

5. fixed-fixed bridge,

6. complex bridge (comprising both fixed-fixed and cantilever bridges). These bridges were excluded from the study because of very small sample sizes (two bridges),

7. cantilever bridge,

8. chip porcelain,

9. veneer with incisal coverage.

c. Number of abutments and pontics for the bridgework.

d: The presence of metal reinforcement in the bridges or single restorations.

e. Type of bases used on the prepared teeth coded as:

1. none: (no lining/base was used),

2. glass ionomer cement,

3. calcium hydroxide,

4. other.

f. Different resin composite luting cements used coded as:

1. Mirage,

2. Insure*,

3. Ultra-Bond,

4. Porcelite*,

5. Sono-Cem,

6. Dicor,

7. Other.

* Used with All-Bond 2 dentine bonding adhesive,

g. Operators were determined by codes 1 and 2.

4.5.4 Basic Problems with the Prepared Tooth

Any basic problem with the prepared tooth was determined in this section as:

a. Root canal filled tooth.

b. Discoloured tooth.

c. Short-term post-operative sensitivity after the insertion of the resin-bonded porcelain restoration.

Information about occlusal contacts, and the presence of opposing dentures (shown in the last section of Form 2) were not included because of insufficient information.

4.5.5 Reasons for Restoration Placement

Information about the reasons for restoration placement were as follows:

a. Restoration requested either by the patient or recommended by the operators.

b. The main reason for placement consisted of either a tooth reason or a restoration reason. Tooth reason refers to tooth problems which led to the construction of a resin-bonded porcelain restoration. These are coded as:

1. tooth loss,

2. tooth fracture,

3. discoloured tooth,

4. tooth wear,

5. RCF tooth,

6. malocclusion,

7. tooth defect,

8. tooth sensitivity,

9. tooth prepared as an abutment.

Restoration reason refers to problems associated with the previous restoration, which might have been a resin composite or an amalgam filling, or a previous resin-bonded porcelain restoration. These reasons are coded as:

1. restoration fracture,

2. recurrent caries,

3. microleakage sensitivity,

4. discolouration,

5. open contacts/food impaction,

6. restoration lost,

7. malocclusion,

8. restoration wear,

9. mercury scare.

4.5.6 Recorded Dates and Restoration Identification

a. Since assessment of the longevity of the resin-bonded porcelain restorations was the most important aim of this study, the date that the restoration was first placed, and the last observation date (if the restoration was still present) or the date when the restoration had failed, were obtained from the casenotes. It should be noted that the term 'restoration placement' refers to when the resin-bonded porcelain restoration was placed for the first time. However, 'replacement' refers to those restorations which were placed because the original resin-bonded porcelain restorations had failed.

b. The restoration number shows both the total number of restorations inserted and the number of times that a particular restoration was replaced. If a restoration was replaced, the restoration suffix number would stay the same while the prefix number (first left number) would change by one. For example, if a restoration failed, then the prefix coding would change from 10156 to 20156, where 0156 represents the restoration number, and the underlined numbers represent the times the restoration was placed (1) or replaced (2).

4.5.7 Failure Data:

a. To give a general idea about the most common problems associated with these restorations, failure types were considered. In this section failures were divided into 'true and apparent failures'. A failure was considered as a 'true failure' when the restoration was replaced or repaired due to persistent post-operative sensitivity, recurrent caries, food impaction, colour mismatch, debonding, bulk or chip fracture, and connector fracture (in bridgework), or when microcracks were present. An 'apparent failure' on the other hand, was recorded when the restoration failed because of unrelated factors such as acute trauma, or when part of a bridge (intact second abutment restoration) had to be replaced because the other abutment restoration was a true failure.

b. Possible failure reasons were listed as: microleakage, poor preparation, poor etch or contamination, poor enamel quantity/quality, occlusal stress, tooth mobility, restoration not seated, poor colour match, and other (eg. trauma). Selection of a particular reason was often merely an educated guess, even after discussion with the operators.

c. Treatment following failures was important in the evaluation of the resin-bonded porcelain restorations. This section provided interesting information about the replacement restorations, and whether or not they were other conservative, or non-conservative types.

d. Provision was made to obtain extra information on restoration deterioration (eg. surface roughness, staining, marginal fracture, colour mismatch,...), and wear information (eg porcelain restoration, opposing teeth/restorations, cement margins, ...). However, these data could not be collected because not enough information was present in the casenotes.

At the end of this stage, colour transparencies were taken of some of the restorations to facilitate the evaluation of different designs, and any differences present between the original restorations and their replacements.

Thirty restorations were selected at random from the same 536 restorations, and the assessments were duplicated to evaluate examiner reliability.

CHAPTER FIVE

Results and Discussions

Introduction

The results and discussions of this study are presented in three sections:

5.1 Preparation dimensions and design,

5.2 Restoration failures, and

5.3 Restorations survivals.

Discussion of each section will be presented at the end of that section. The results of restoration failures and survivals will be discussed in one section (5.3.3).

5.1 SECTON ONE - PREPARATION DIMENSIONS AND DESIGN

As the thickness of porcelain appears to be an important criterion for the strength and survival of resin-bonded porcelain restorations, different aspects of preparation dimension were measured. In this chapter, the in vitro results of posterior preparation dimensions and design are presented. These results will then be compared with reports in the dental literature.

5.1.1 General Data

As mentioned previously, only the stone die preparations of posterior single restorations (shell crown, onlay, inlay) were collected for this part of the study. Tables of the results for preparation dimensions and characteristics are shown in Appendix III. The distribution of restorations in the maxilla and mandible is shown in Table 1. Out of 105 restorations, 46 were shell crowns, 57 were onlays, and only two were inlays.

Of 105 restorations, 20% were shell crowns located in the maxilla, with 24% located in the mandible; and 29% were onlays located in the maxilla, with 25% in the mandible. Although the distribution of both types of restorations in the mandible were similar, relatively more onlays were located in the maxilla. Since the sample size for the inlays was very small, they were excluded from the study.

From 103 shell crowns and onlays, 25 failed (11 shell crowns and 14 onlays), (Table 2). Eight of the failed onlays were located in the maxilla, and six were located in the mandible. Of the 11 failed shell crowns, two were in maxillary, and nine were in mandibular teeth. Failure occurred more frequently in molar teeth. Represented in Table 3 is the failure type of shell crown and onlay restorations. In both types of restorations, bulk fracture and pulpitis were reported more frequently. Occurrences of debonding and chip fracture were very low in these 103 restorations.

Table 4 shows the percentages of different tooth surfaces involved in the preparations of each type of restoration to give some idea of the design of the restorations. However, since in shell crowns all of the tooth surfaces were prepared, the number of surfaces involved in these restorations is listed as 'all surfaces', regardless of any existing occlusal or proximal boxes. As can be seen in the table, MOD preparations were the dominant tooth surfaces involved in the onlay restorations. In 7.6% of instances, the onlay preparations extended part way down the buccal and lingual tooth surfaces.

In many instances, the onlays and shell crowns were reinforced occlusally with metal inserts fused to the porcelain. Unsupported porcelain extended peripheral to the metal inserts, to avoid compromising the aesthetics of the restorations (Figure 12, Chapter 4).

5.1.2 Measurements

As also mentioned previously, different aspects of the preparations were measured at the mesial and distal sites of premolar and molar teeth to determine any differences in cavity size and design at these sites. The total numbers of measurements in each table were different because the number of surfaces involved for each preparation differed from one tooth to the another. Average, maximum, minimum, and the standard deviations of the measurements for each group are given in the tables. The preparation dimensions of failed restorations are presented in separate tables for comparison with surviving restorations. Only the preparation dimensions of those 12 restorations with bulk fracture (five shell crowns, and seven onlays) are shown in the present section, since bulk fracture is more relevant to the preparation dimension. Therefore, the term 'failed' refers to the restorations with bulk fracture.

5.1.2.1 Intercuspal Width

Intercuspal width measurements of preparations for surviving shell crown and onlay restorations are shown in Tables 5a and 6a. For shell crown restorations, the average intercuspal width measurements for premolar teeth were 4.6 mm in mesial, and 5.0 mm in distal sites (Table 5a). The average intercuspal widths for molar teeth were 5.7 mm and 6.8 mm in mesial and distal sites, respectively. The maximum intercuspal width measured was 6.3 mm for premolars, and 7.0 mm for molars. The minimum measurement was 3.0 mm for premolars, and 3.9 mm for molars. Table 5b shows the same measurements for failed shell crowns. A comparison of average intercuspal widths in intact and failed shell crowns showed no marked differences between the two groups. Minimum and maximum dimensions measured in both groups were approximately in the same range.

For intact onlay restorations, the average intercuspal width measurements for premolars were 4.5 mm and 6.1 mm in mesial and distal sites (Table 6a). The same measurements for molars were 5.8 mm in mesial and distal sites, respectively. The maximum intercuspal width measured was 7.1 mm for premolars, and 7.5 mm for molars. The minimum measurement of intercuspal width for premolars was 3.5 mm, and for molars was 4.0 mm. The average intercuspal widths for surviving and failed onlays (Table 6b) were not significantly different.

As can be seen from the tables, only small differences existed between the shell crown and onlay preparations. In each group the preparations appeared to be larger in the distal than in the mesial sites.

The most common distribution of measurements for surviving shell crowns was between 4.0-5.9 mm, while it was more than 6.0 mm for failed shell crowns (Diagrams 1a and 1b). In onlays, the intercuspal width dimensions were mostly more than 6.0 mm in both failed and surviving restorations (Diagrams 2a and 2b).

5.1.2.2 Isthmus Width

Isthmus width was measured in mesial and distal sites of premolars and molars for both the shell crown and onlay restorations. The average isthmus width for surviving shell crowns were 3.6 mm and 3.9 mm in mesial and distal sites of premolars, and 3.8 mm and 4.2 mm in mesial and distal sites of molars, respectively (Table 7a). The isthmus widths ranged from 2.2- 4.8 mm in premolars, and from 2.7- 5.5 mm in molars. For failed shell crowns, there was no occlusal step or slot to measure isthmus width in the premolars (Table 7b). The average isthmus width in distal sites of failed shell crowns was larger than that for surviving shell crowns in molar teeth, as were the minimum and maximum isthmus widths.

The average isthmus width for intact onlay restorations was 3.1 mm in mesial and 3.7 in distal sites of premolars, and 3.1 mm in mesial and 3.8 mm in distal sites of molars, respectively (Table 8a). The minimum isthmus width measured in premolars and molars was 1.2 mm and 0.5 mm, respectively. The maximum isthmus width was 4.9 mm in premolars and 5.4 mm in molars, respectively. When comparing isthmus width dimensions in surviving and failed onlays, no significant differences were found between the two groups (Table 8b).

The average isthmus widths in premolars and molars for shell crowns were not markedly different from those of onlays. The minimum isthmus widths were the same for both shell crown and onlay restorations. Minimum isthmus widths for both failed shell crowns and onlays were generally larger than that in surviving restorations. The cavities had slightly wider isthmuses in distal than in mesial sites.

Diagrams 3a and 3b show the distribution of isthmus width measurements in intact and failed shell crown restorations. The distribution of measurements was approximately the same in both groups (≥4.0 mm). Isthmus width was distributed between 3.0-3.9 mm in surviving, and ≥4 mm in failed onlays (Diagrams 4a and 4b).

5.1.2.3 Proximal Width

Proximal width dimension had an average of 4.6 mm and 4.4 mm in mesial and distal sites of premolars, and 4.5 mm and 5.6 mm in mesial and distal sites of molars for shell crown restorations (Table 9a). Minimum proximal width was 3.6 mm and 3.5 mm in premolars and molars, respectively. The maximum dimension measured in premolars was 5.9 mm, and in molars 6.8 mm, respectively. The number of proximal width measurements for failed shell crowns was very small (Table 9b). The average proximal width for failed and surviving shell crowns was approximately the same (Table 9b). However, maximum proximal widths for surviving shell crowns were much larger than failed shell crowns.

The average proximal width measurements for intact onlays were 4.8 mm in mesial and 5.4 mm in distal sites of premolars (Table 10a). These measurements were 4.8 mm and 4.9 mm in mesial and distal sites of molars, respectively. Proximal widths ranged between 2.1- 6.8 mm for intact onlays, and 3.4- 6.2 mm for fractured onlays. The average proximal widths in failed and surviving onlays were approximately similar (Table 10b). The distal measurements were generally larger than the mesial for both shell crowns and onlays.

Proximal width measurements for surviving shell crown restorations were distributed approximately equally across the interval ranges (Diagram 5a), as were the measurements for failed shell crowns (Diagram 5b). In onlay restorations, however, proximal width measurements were mostly distributed between 4.0-5.9 mm for both failed and surviving groups (Diagrams 6a and 6b).

5.1.2.4 Height of Axial Wall

The results of height of axial wall measurements for surviving shell crown and onlay restorations are shown in Tables 11a and 12a. The average dimensions for shell crowns were 2.8 mm in mesial and 3.4 mm in distal sites of molars. Height of axial walls ranged from 1.5- 4.8 mm for surviving, and from 1.2- 3.8 mm for failed shell crowns.

Only three axial walls were found for surviving shell crowns in premolar teeth (two in mesial and one in distal sites). Therefore, the measurements cannot be used for any comparisons and were excluded from Table 11a. The maximum dimensions measured were 3.7 mm in mesial, and 4.8 mm in distal sites of molar teeth. Average, maximum and minimum height of axial walls for failed shell crowns are presented in Table 11b. The dimensions were very similar for both the intact and failed shell crowns.

The average heights of axial walls measured for surviving onlay restorations were 2.3 mm in mesial and 2.6 mm in distal sites of premolars, and 2.7 mm and 3.0 mm in mesial and distal sites of molars (Table 12a). The height of axial wall dimensions ranged from 1.8- 3.6 mm in premolars, and 1.3- 4.9 mm in molars. The axial wall heights for fractured onlays were almost the same as those for surviving onlays (Table 12b). Preparations were larger in distal than mesial sites for both shell crown and onlay restorations.

The measurements were mostly distributed between 2.0-2.9 mm for intact and failed shell crowns (Diagrams 7a and 7b). While the measurements were usually between 2.0-2.9 mm for intact onlays, they were usually between 2.0-3.9 mm for failed onlay restorations (Diagrams 8a and 8b).

5.1.2.5 Depth of Occlusal Floor from Central Fissure

Depth of occlusal floor from the central fissure (or opposing cusp tip) is a very important aspect of preparation dimension since it shows the thickness of the restoration at this point. The average dimensions of intact shell crowns without metal reinforcement were 2.8 mm in mesial sites of premolars, and 3.9 mm in mesial and 3.0 mm in distal sites of molars (Table 13a). The thinnest areas measured were 0.9 mm in premolars, and 1.9 mm in molars. The thickest areas measured were 5.7 mm and 6.1 mm in premolars and molars, respectively. Generally, more tooth reduction was expected for restorations with metal reinforcement. However, reduction was greater for shell crowns without metal reinforcement, when comparing the average and maximum values for shell crowns with metal reinforcement (Table 13b). Preparations were mostly distributed between 2.0-2.9 mm in both groups (Diagrams 9a and 9b). Table 13c shows the depth of occlusal floor measurements for failed shell crowns. There was no molar and premolar category in this table because of the very small sample sizes when they were divided into four subgroups (molar and premolar, with and without metal reinforcement). Therefore, they were considered as posterior teeth only, since no significant difference was found between depth of occlusal floor in molar and premolar teeth. For this reason, a valid comparison with two other groups (Tables 13a and 13b) is difficult. Generally speaking, the depth of occlusal floor for failed shell crowns was larger than that of surviving shell crowns. A few large tooth reductions at the central fissures for fractured shell crowns caused this difference which is evident from the large standard deviation. The measurements were most frequently distributed between 3.0-3.9 mm (Diagram 9c).

The maximum and minimum depths of occlusal floor were markedly different for surviving onlays, with and without metal reinforcement (Tables 14a and 14b). While the thickest areas of onlays without metal reinforcement were generally larger than those of onlays with metal, the thinnest areas were much smaller than those for onlays with metal. Depth of occlusal floor for failed onlays is presented in Table 14c. The depth of the occlusal floor was not significantly different between the with and without metal reinforcement groups for failed onlays. However, the depths were slightly smaller than for related groups of surviving onlays (Tables 14a and 14b). The measurements were dominantly distributed between 2.0-2.9 mm in all three groups (Diagrams 10a, 10b and 10c). An example of an onlay preparation with large depth of occlusal floor on a root canal filled tooth is shown in Figure 1.

5.1.2.6 Cusp Reduction

Another important preparation dimension is cusp reduction, which represents the thickness of the restoration at the cusp tips. In this study, cusp reductions were measured on the working side only because of the importance of these cusps in function and also, as mentioned in section 4.1.3c, the impressions gave spurious result for the non-working side cusp reduction dimensions.

The average amount of cusp reduction was recorded as 1.9 mm in mesial sites of premolars, and 1.7 mm in mesial and distal sites of molars, for intact shell crowns without metal reinforcement (Table 15a). For shell crowns with metal reinforcement, cusps had an average reduction of 2.0 mm in mesial sites of premolars, and 2.2 mm and 2.9 mm in mesial and distal sites of molars, respectively (Table 15b). The amount of cusp reduction for shell crowns with metal reinforcement was generally more than for shell crowns without metal reinforcement. The most usual distribution of cusp reduction was between 1.0-1.9 mm for shell crowns without metal, and 1.0-3.9 mm for shell crowns with metal reinforcement (Diagrams 11a and 11b). The average cusp reduction for fractured shell crowns with and without metal was not markedly different (Table 15c). The dimensions of cusp reduction for failed shell crowns were in the same range for surviving shell crowns. The amount of cusp reduction was most often distributed between 2.0-2.9 mm for failed shell crowns (Diagram 11c).

The average cusp reduction for onlays with metal reinforcement was slightly larger than that for onlays without metal reinforcement (Tables 16a and 16b). In both groups the cusp reduction measurements were most often distributed between 1.0-2.9 mm (Diagrams 12a and 12b). Cusp reduction less than 1.0 mm was common for onlays without metal reinforcement, which was not seen in the any other groups (Table 16a). The average cusp reduction for failed onlays was not significantly different from the surviving restorations. The cusp reduction for failed onlays was in the range of surviving onlays (Table 16c). Most cusps were reduced between 1.0-2.9 mm for the failed onlays, which was the same as for the intact restorations (Diagram 12c).

5.1.3 Preparation Characteristics

All preparation characteristics were again evaluated at the mesial and distal sites of premolar and molar teeth to determine if there were any differences in preparation design at each proximal surface of these teeth. The results are presented in Tables 17a and 17b for shell crown, and in Tables 18a and 18b for onlay restorations. Preparation characteristics of failed restorations included all types of failures (from 25 restorations), since no obvious differences were found between the preparation features in different types of failed restorations.

5.1.3.1 Gingival Margin in Dentine or Enamel

Since bonding to dentine or cementum is not as reliable as it is to enamel, margins finished in dentine or cementum were evaluated in this section. For intact shell crown restorations, a total average of 9% of the preparation margins were located in dentine (Table 17a). This percentage was 4.7 for intact onlay preparations (Table 18a). None of the margins in failed shell crowns and onlays was located in dentine (Tables 17b and 18b).

5.1.3.2 Margins Bevelled Occlusally or Gingivally

Because of the importance of finishing lines, the existence of any bevelled margins in the preparations were examined. For the shell crown preparations in premolars and molars, around 7% of surviving, and 13% of failed restorations on average had some evidence of minimally bevelled gingival margins. For the onlay preparations, an average of 12% and 23% of gingival margins had been minimally bevelled in intact and failed restorations, respectively. In several instances, the gingival margin bevelling was incomplete, and the distinction between bevelled and chamfered margins was uncertain. Apart from at the sites of gingival proximal boxes, all other margins were prepared as heavy chamfers. Bevelled gingival margins were less evident at distal sites.

5.1.3.3 Opposing Tooth Contact at Restoration Margins

For intact shell crown restorations, an average of 1.4% of preparations had contacts with opposing teeth at the margins which was found in molars only. For the intact onlays, an average of 9.3% of preparations had marginal contacts with opposing teeth. There was no opposing tooth contacts with restoration margins for failed shell crowns and onlays.

5.1.3.4 Angular Cavosurface Margins

None of the shell crown and onlay preparations had sharp, angular cavosurface margin outlines. All outlines were curved and blended into one another.

5.1.3.5 Sharp Internal Line or Point Angles

None of the shell crown and onlay preparation had any sharp internal line angles.

5.1.3.6 Retention boxes

With a reliable bond to tooth structure, no extra retention should be necessary in resin-bonded porcelain restorations. In the evaluation of the dies, any existing shallow boxes in the preparations (Figure 2), were recorded as retention boxes until further discussions were made with the operators. For shell crowns, 4.3% and 13% of the preparations on average had retention boxes in intact and failed restorations, respectively. For onlays, retention boxes existed in an average of 5.8% of surviving, and 15% of failed restorations. There was no pattern for sites.

5.1.3.7 Metal Reinforcement

Application of metal reinforcement was evaluated because of its effect on restoration strength. Some 60% of premolars, and 50% of molars had shell crowns with metal reinforcement, which did not fail (Table 17a). For failed shell crowns, 43% of premolars and 25% of molars had metal reinforcement (Table 17b), which was markedly less than for the nonfailed shell crowns, but the numbers were small. The percentages of intact onlays with metal reinforcement (18% and 19% in premolars and molars, respectively, Table 18a) were considerably less than for the shell crowns (60% and 50% in premolars and molars, respectively). None of the few failed onlays in premolars had metal reinforcement, whereas 25% of the failed onlays in molars had a metal substructure (Table 18b).

5.1.3.8 Preparation Taper

Preparation taper is generally regarded as a very important aspect of design, since there is considerable emphasis on restoration retention and the amount of tooth reduction relating to taper in the literature. For intact shell crowns, an average of 64% of preparation tapers were less than 20° (Table 17a). This was 43% for failed shell crowns (Table 17b). An average of 17% of intact (Table 18a), and 45% of failed onlays (Table 18b) had been prepared with less than 20° taper. Preparation taper in premolars and molars was mostly between 21°-40° for intact onlays, and 10°-20° for failed onlays (Table 19 and 20). Preparation taper for intact and failed shell crowns was often less than 20° (Table 19 and 20). The distribution of preparation taper is shown in Diagrams 13a and 13b for intact and failed restorations, respectively. Large (> 20°) and small (< 20°) preparation tapers on molar and premolar teeth are shown in Figures 3 to 7.

5.1.4 Examiner Reliability

The Kappa values for the general features of the stone dies ranged from 0.53 - 1.00, while the probability values of the paired t-tests for the measurements taken from the stone dies ranged from 0.09 - 1.00. The results from Form 1 are shown in Appendix VI. The results of Kappa values show good to excellent agreements for examiner reliability. Paired t-tests revealed no significant differences between any of the original and duplicate measurements.

5.1.5 Limitations of the Study

As described previously, there were limitations present in the degree of accuracy of the measurements and observations made. Taking measurements on small dies of the prepared teeth with an ordinary dial calliper and protractor was difficult and, some measurements were retaken several times. Since the preparations were extremely variable in shape and size, using the same reference points to take the measurements for all dies was also sometimes difficult.

For measuring the depth of the occlusal floor, and the working-side cusps reduction, a silicone putty impression of the dies was taken while they were occluded with the opposing cast. Accurately occluding the upper and lower casts was sometimes difficult, especially in partially edentulous arches.

In some instances, there was uncertainty in distinguishing bevelled from chamfered preparation margins, and the presence of bevelled gingival margins in proximal boxes.

Although there were relatively few dies for restorations which subsequently failed from fracture, this mirrored the actual clinical situation.

Figure 1- Depth of occlusal floor from central fissure in an onlay design without metal reinforcement prepared on a root canal filled tooth (16).

Figure 2 - Retention slots in an onlay preparation of a molar tooth (26).

Figure 3- Large external preparation taper (>40°) in an onlay design without metal reinforcement of a molar tooth (17).

Figure 4 - Large external preparation taper (>40°) in a shell crown design without metal reinforcement of a molar tooth (36).

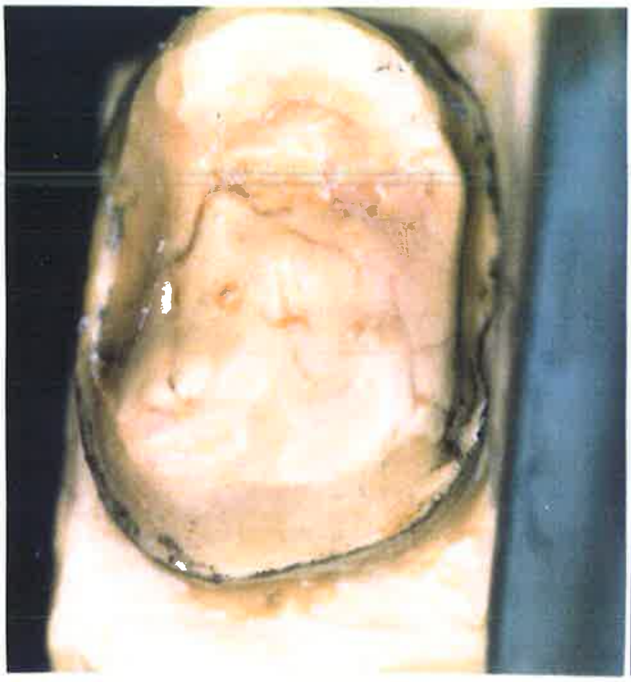


Figure 5- External preparation taper (>20°) in a shell crown design without metal reinforcement of a molar tooth (17).

Figure 6 - Internal preparation taper (<20°) in a shell crown design without metal reinforcement of a premolar tooth (25).

Figure 7- Internal preparation taper (<20°) in an onlay design of a premolar tooth (25).

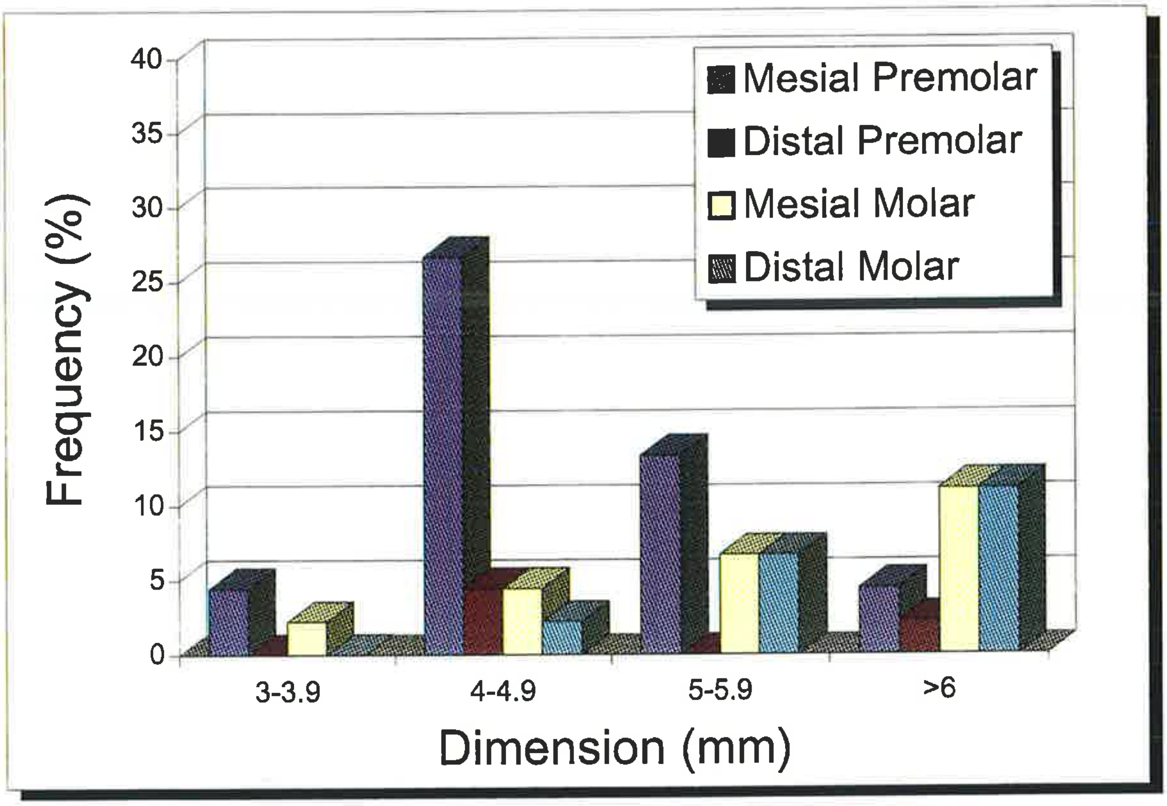


Figure 1a - Intercuspal width in mesial and distal of molar and premolar teeth in intact Shell Crowns (N=45).

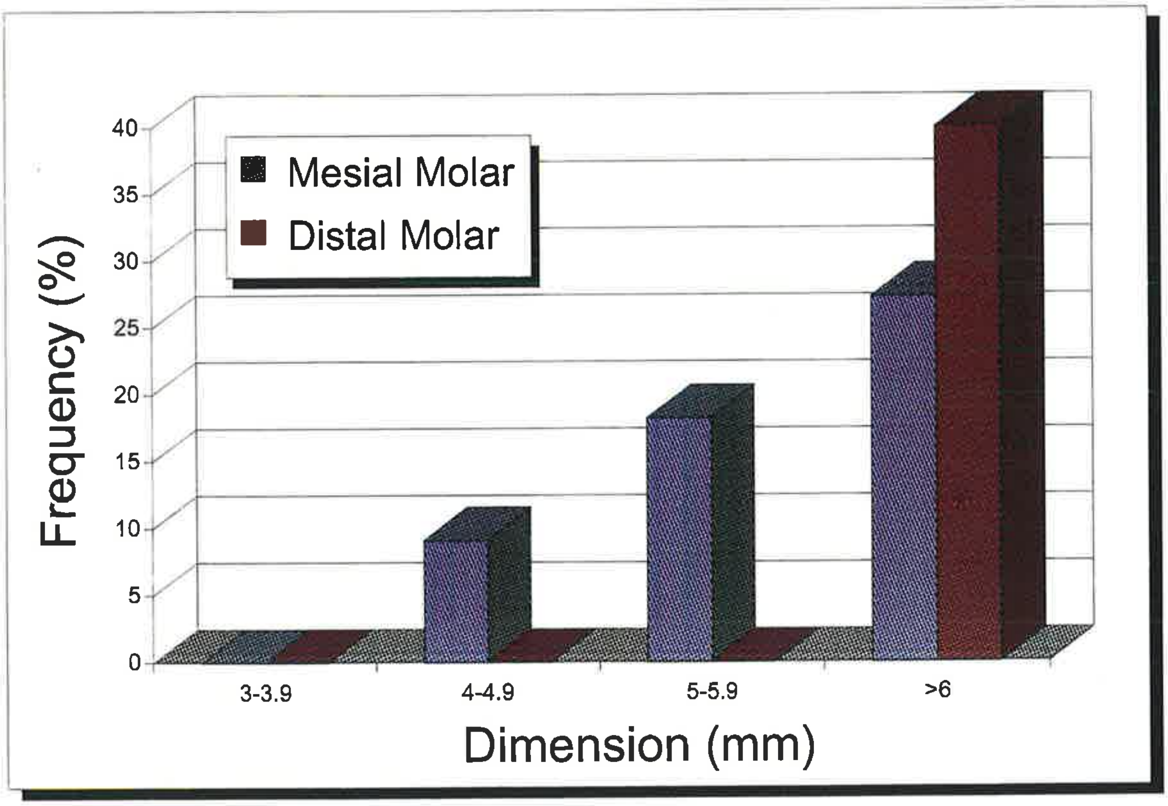


Figure 1b - Intercuspal width in mesial and distal of molar teeth in failed Shell Crowns (N=11).

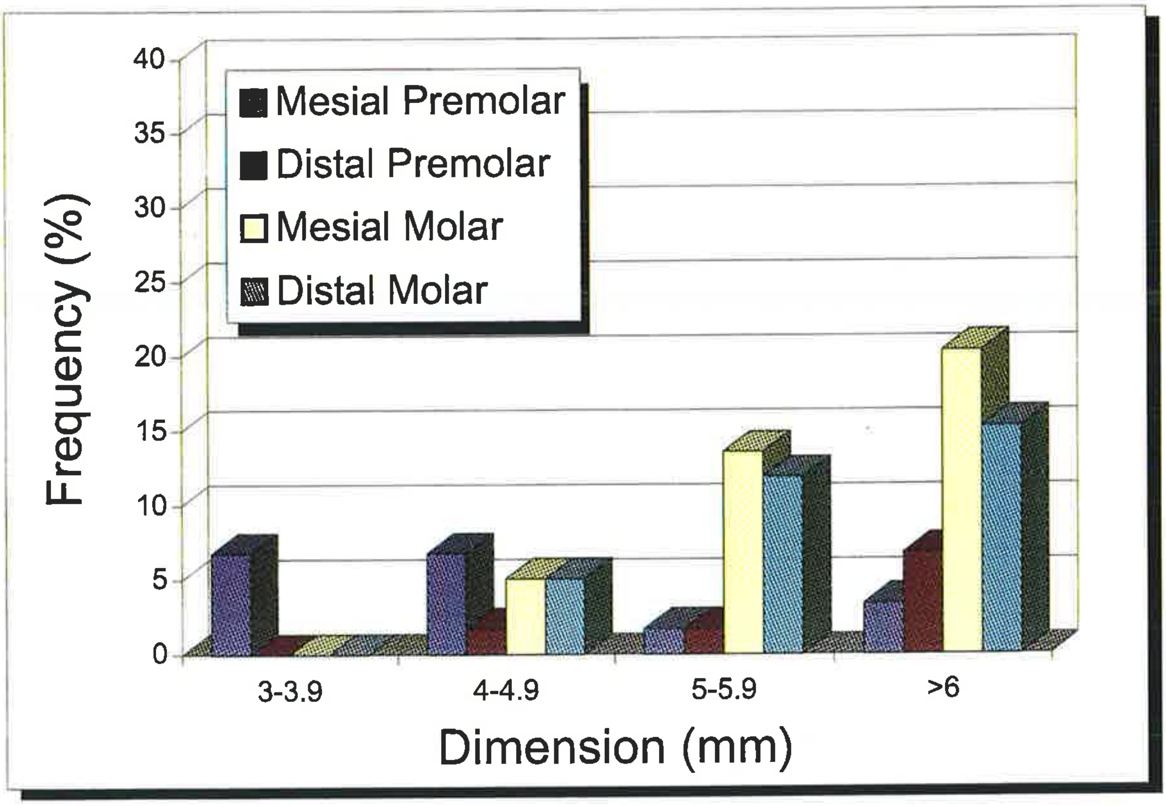


Figure 2a - Intercuspal width in mesial and distal of molar and premolar teeth in intact Onlays (N=59).

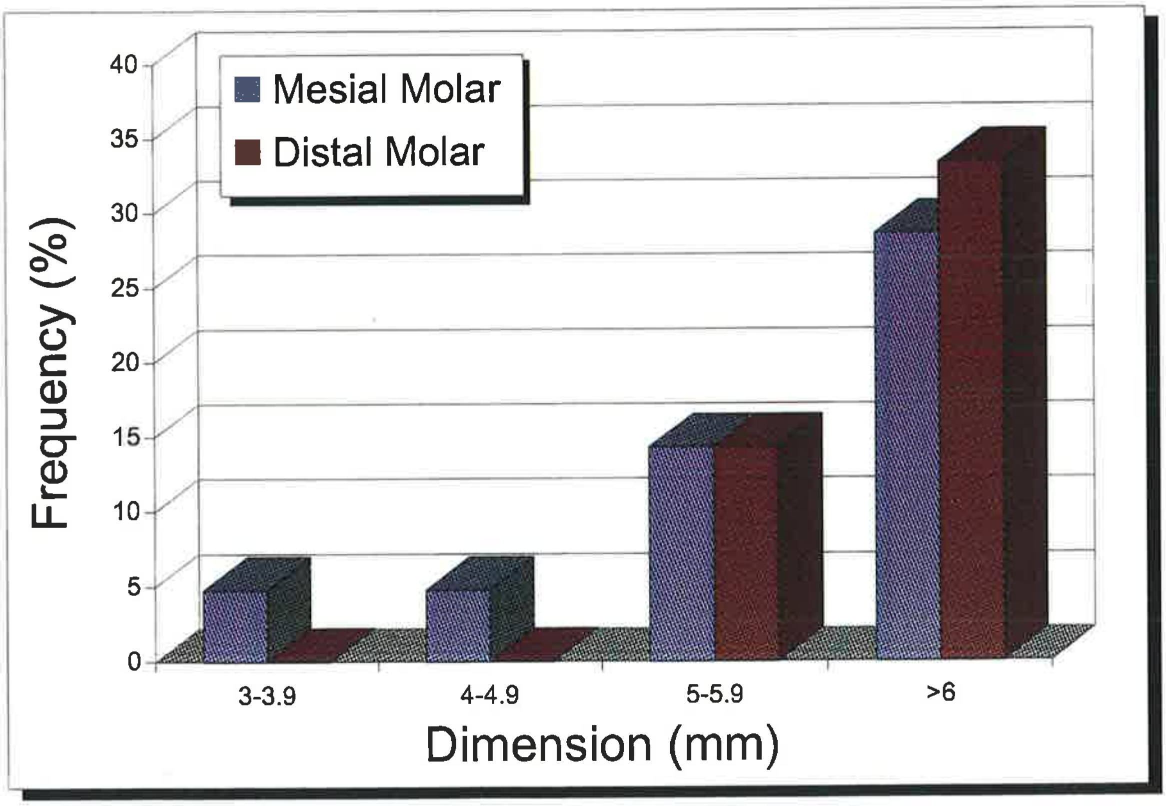


Figure 2b - Intercuspal width in mesial and distal of molar teeth in failed Onlays (N=21).

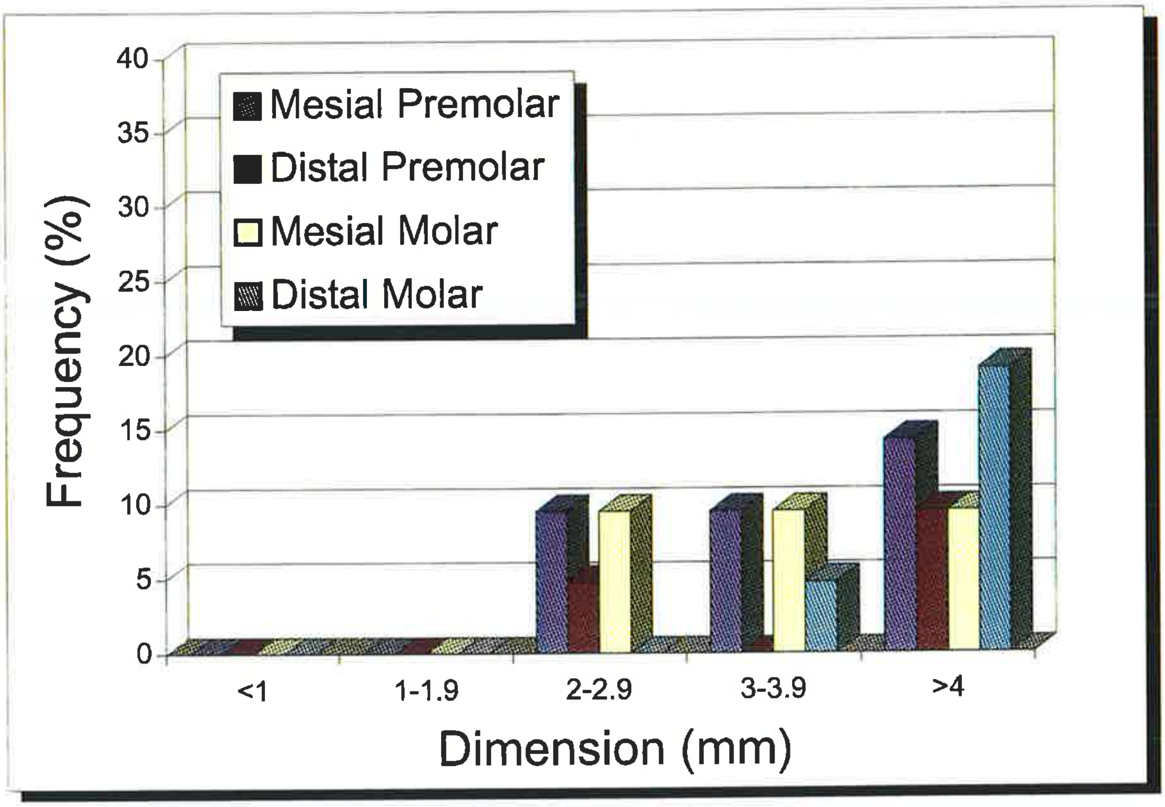


Figure 3a - Isthmus width in mesial and distal of molar and premolar teeth in intact Shell Crowns (N=21).

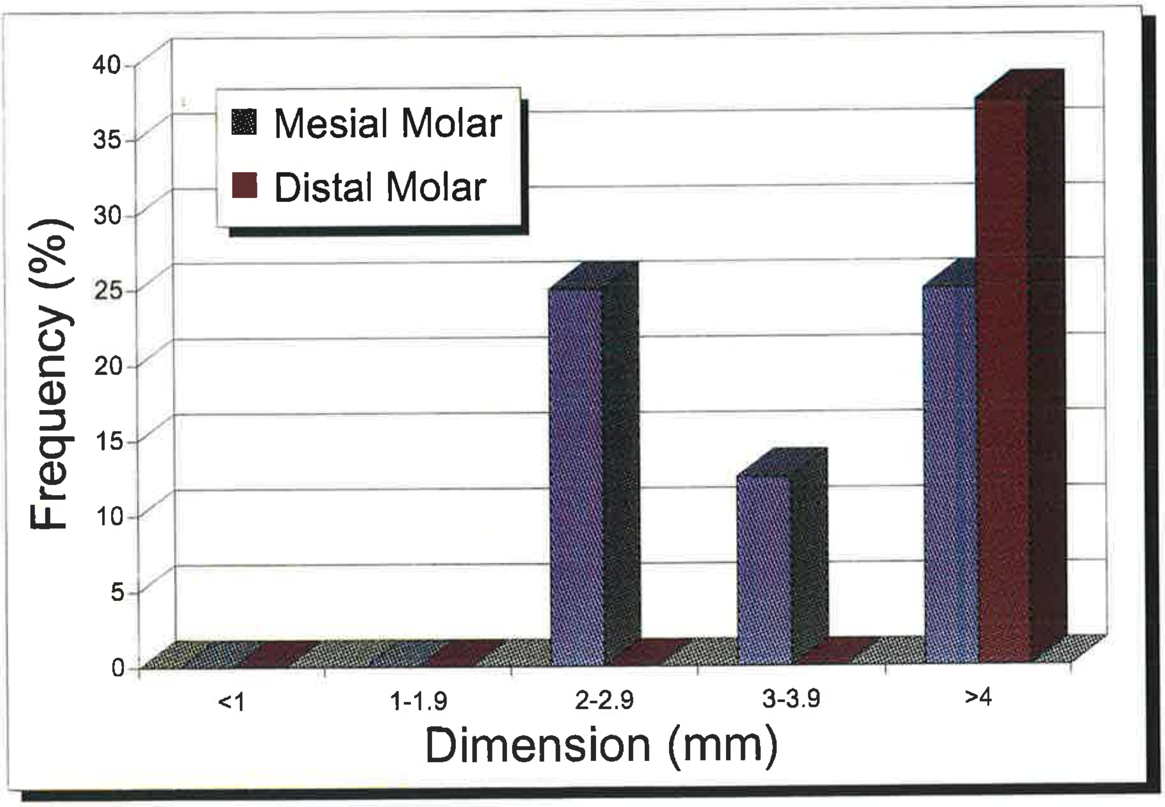


Figure 3b - Isthmus width in mesial and distal of molar teeth in failed Shell Crowns (N=8).

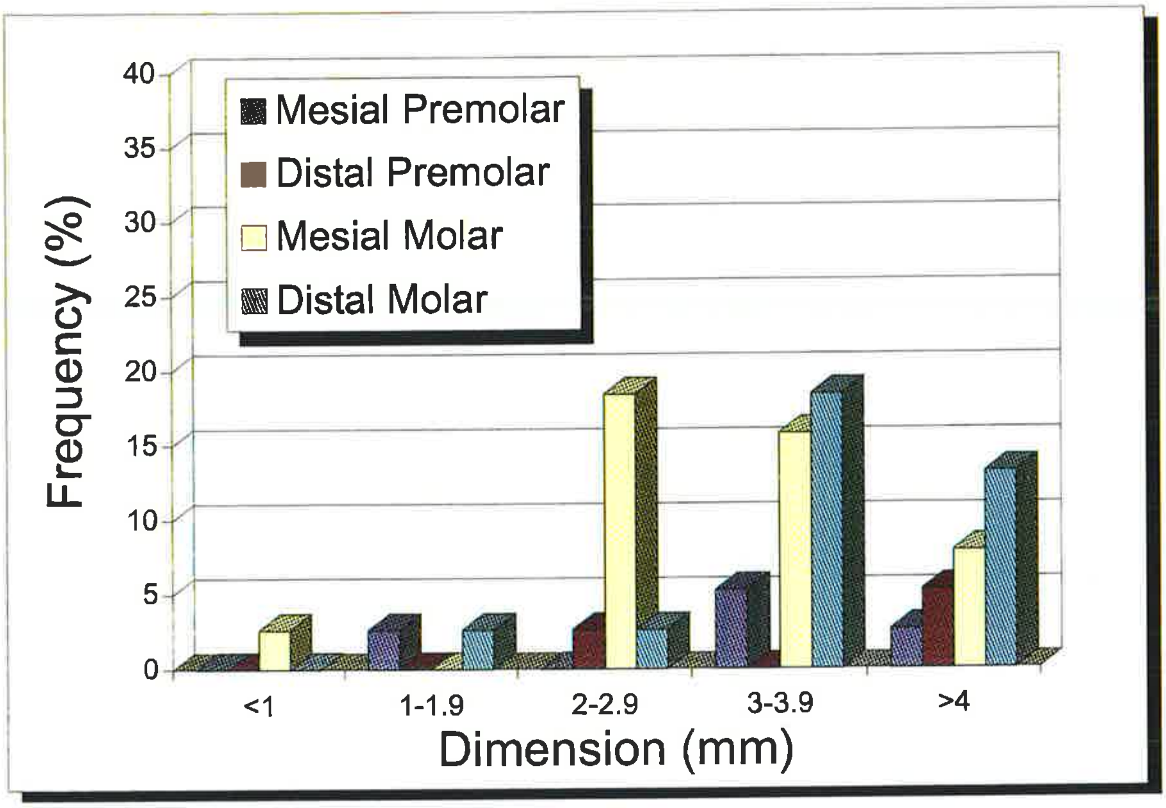


Figure 4a - Isthmus width in mesial and distal of molar and premolar teeth in intact Onlays (N=38).

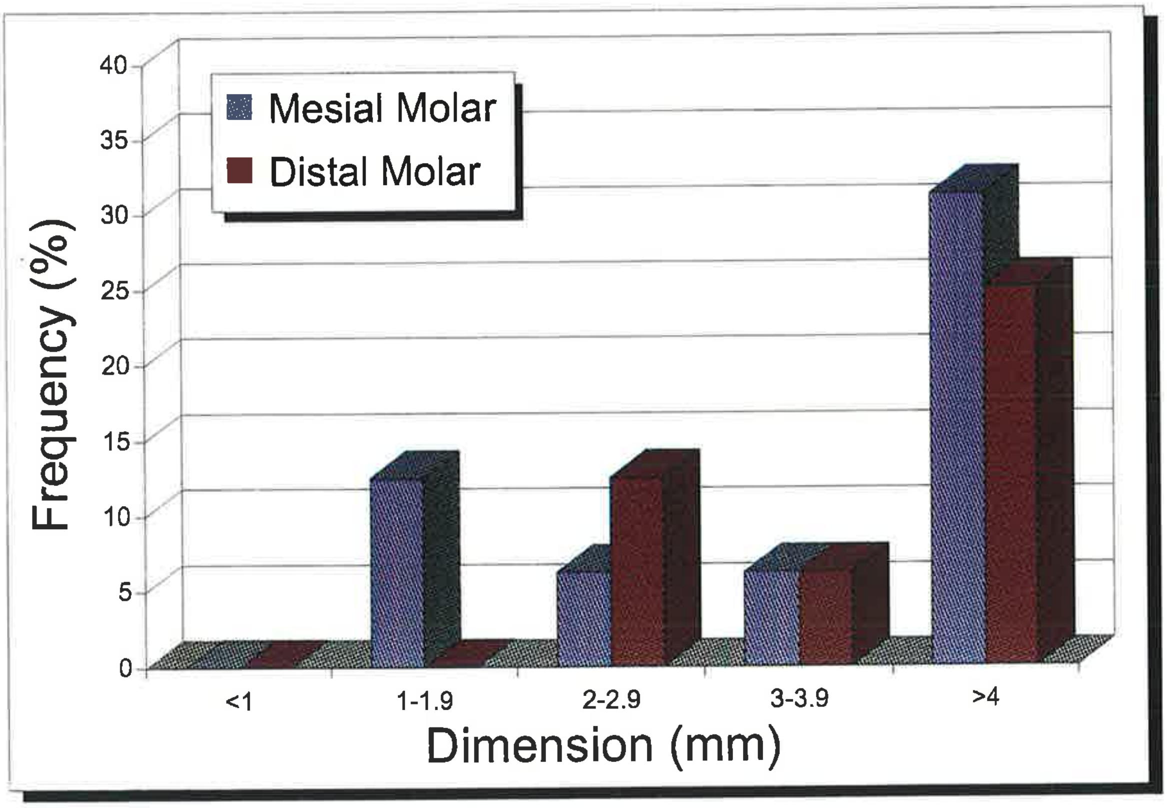


Figure 4b - Isthmus width in mesial and distal of molar teeth in failed Onlays (N=16).

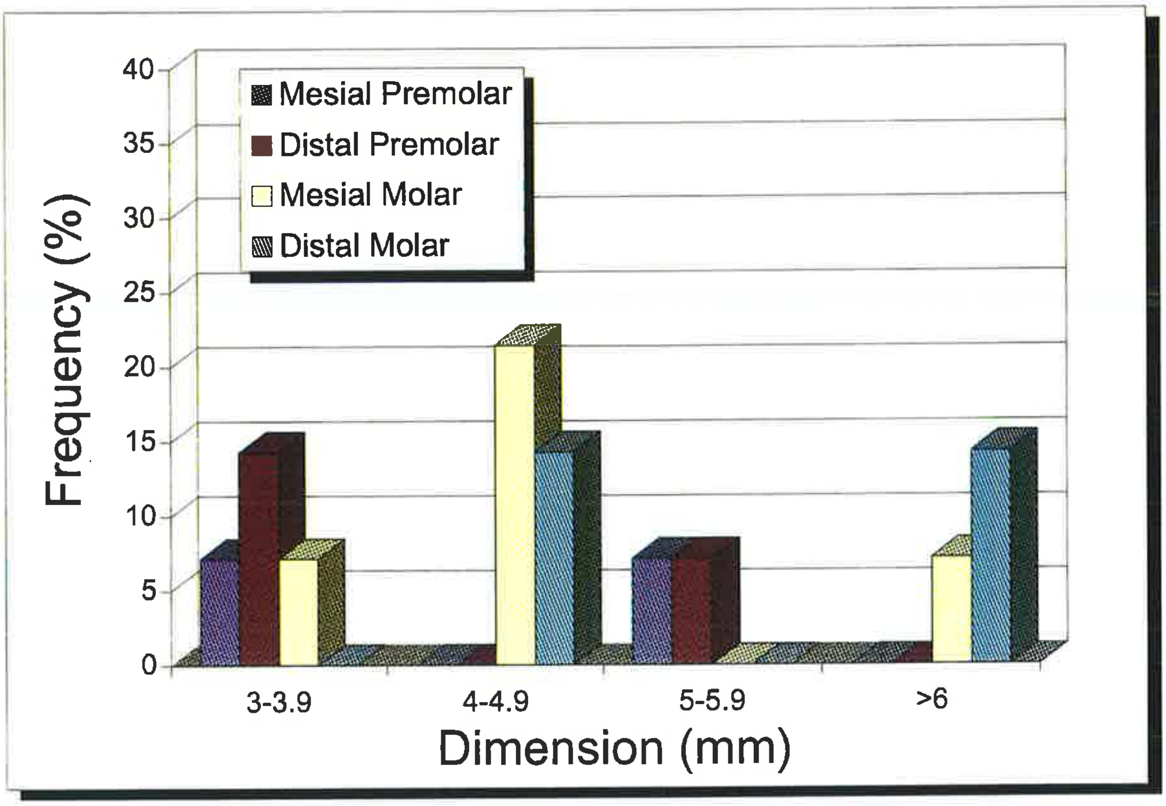


Figure 5a - Proximal width in mesial and distal of molar and premolar teeth in intact Shell Crowns (N=14).

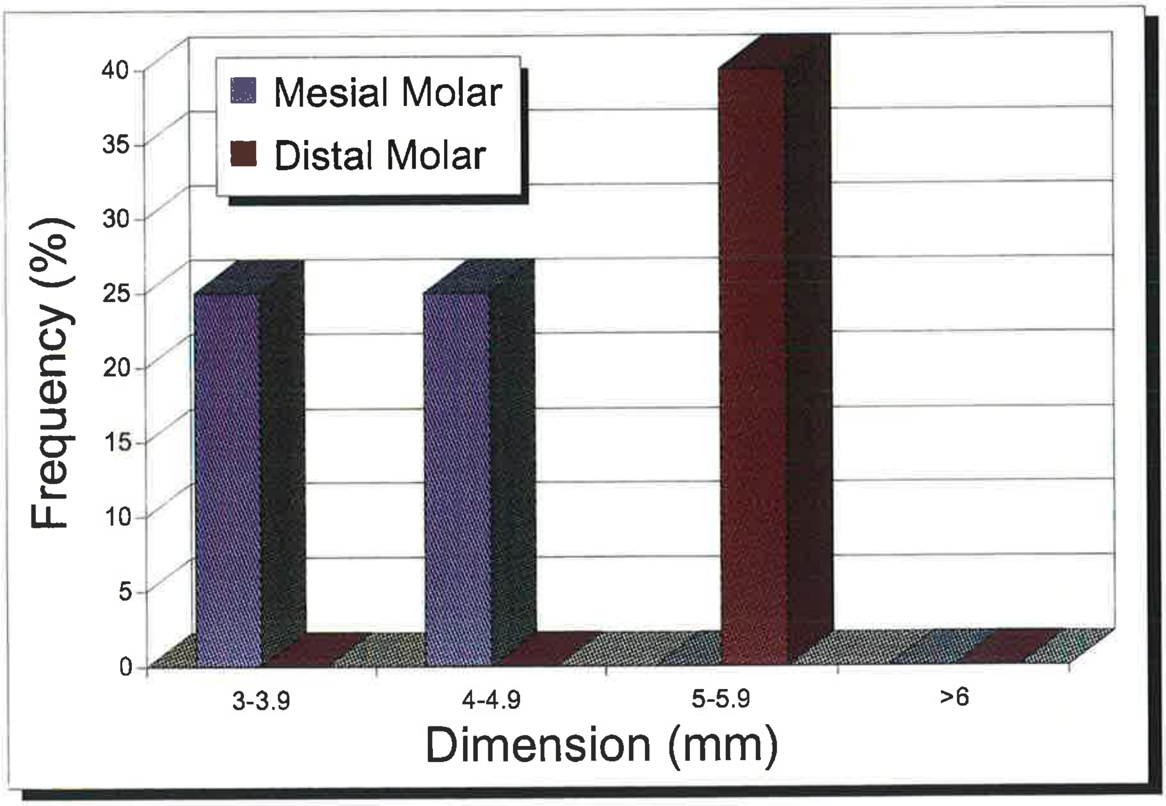


Figure 5b - Proximal width in mesial and distal of molar teeth in failed Shell Crowns (N=4).

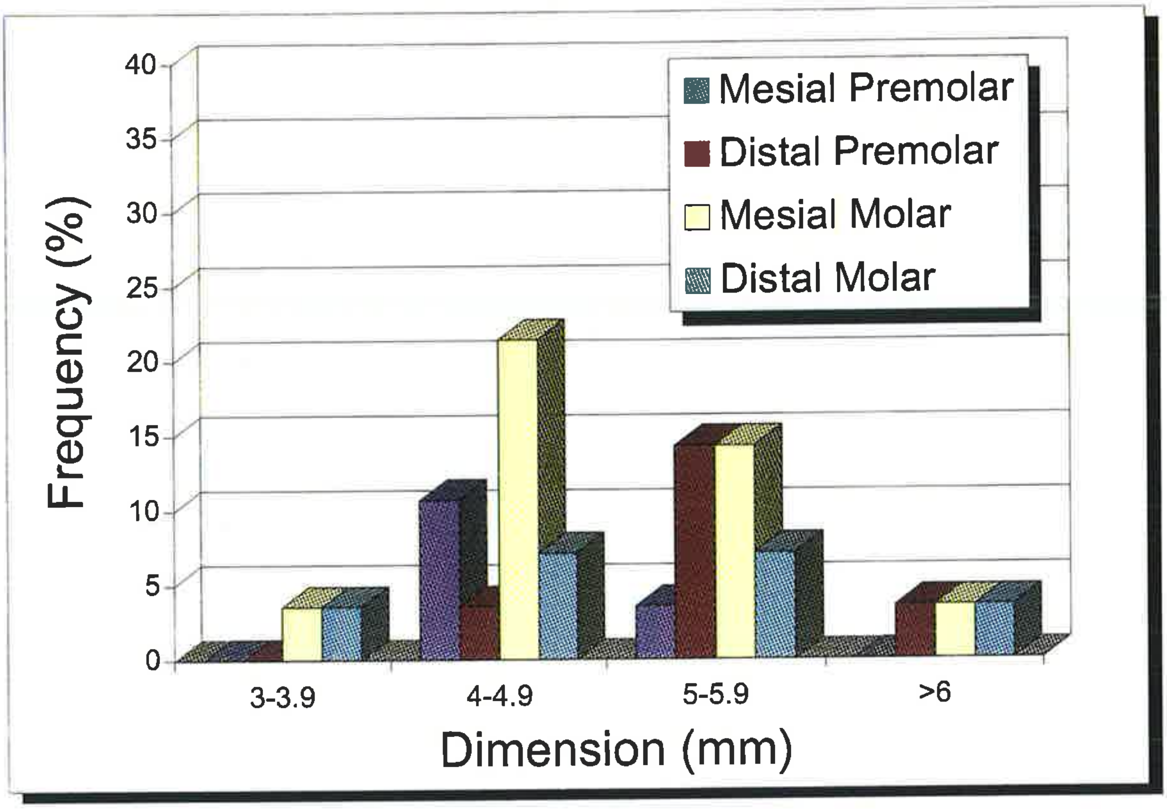


Figure 6a - Proximal width in mesial and distal of molar and premolar teeth in intact Onlays (N=28).

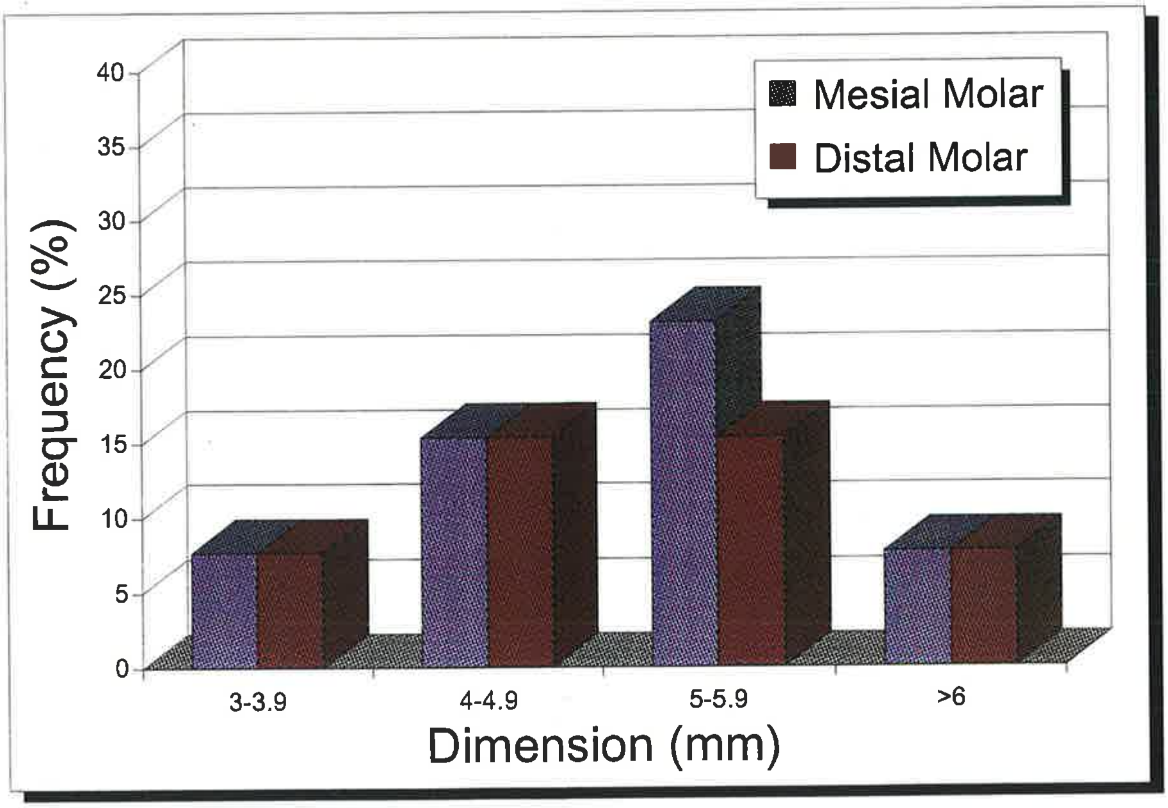


Figure 6b - Proximal width in mesial and distal of molar teeth in failed Onlays (N=13).

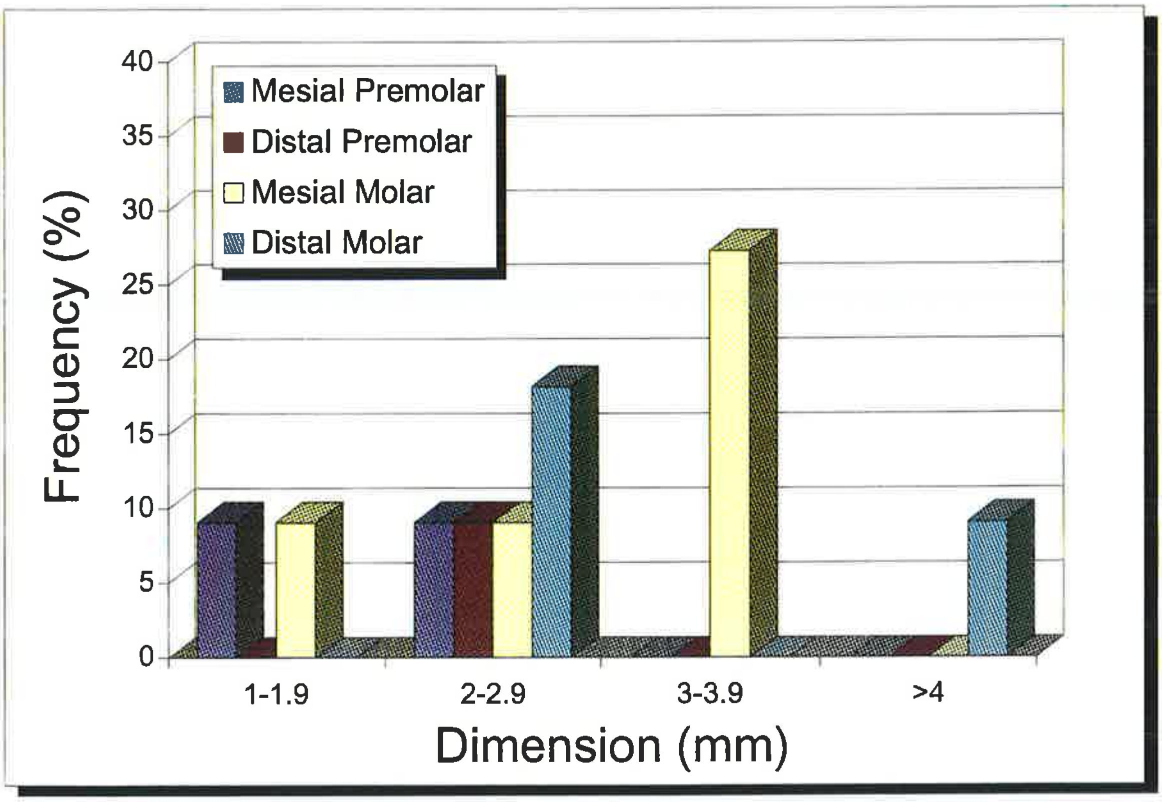


Figure 7a - Height of axial wall in mesial and distal of molar and premolar teeth in intact Shell Crowns (N=11).

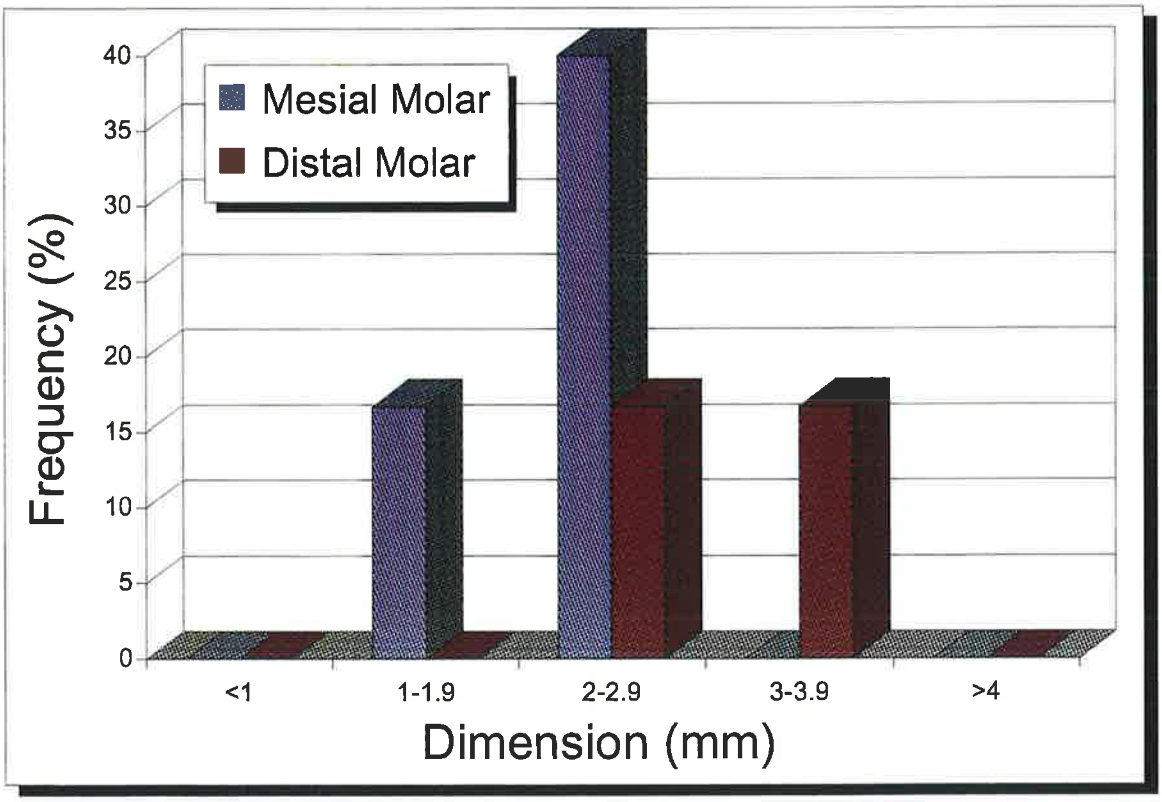


Figure 7b - Height of axial wall in molar teeth in failed Shell Crowns (N=6).

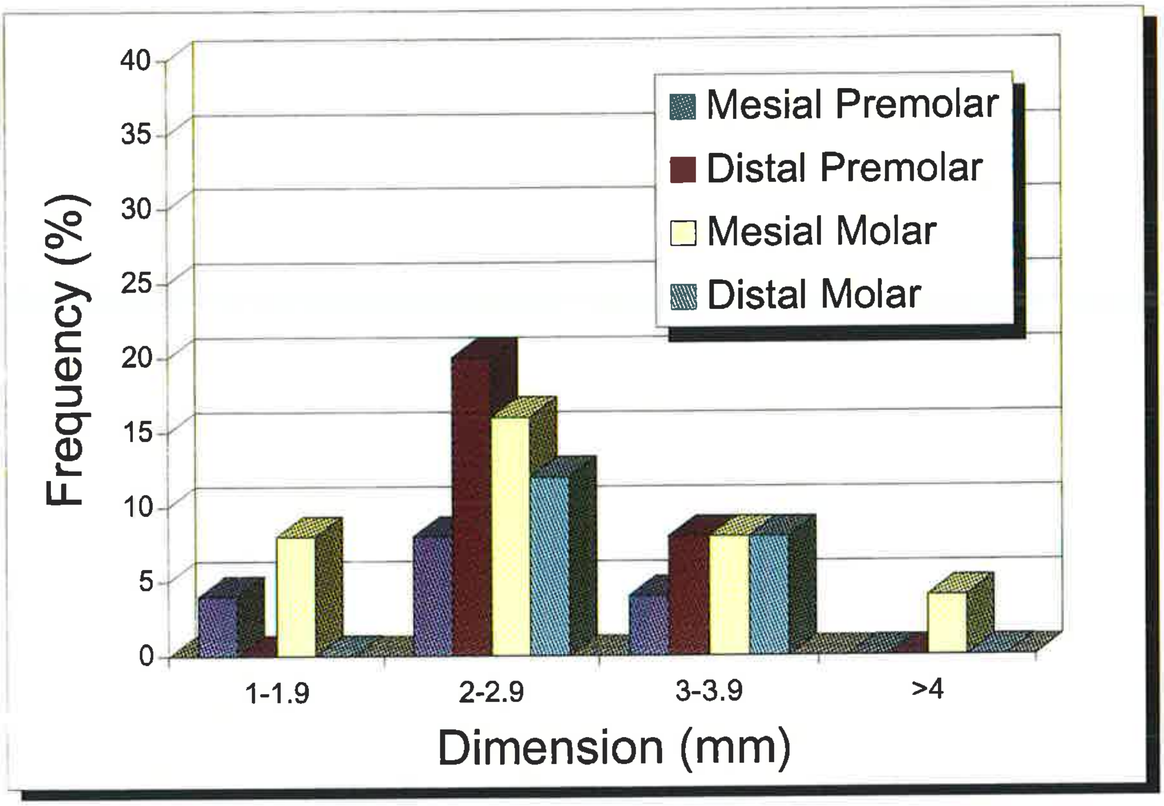


Figure 8a - Height of axial wall in mesial and distal of molar and premolar teeth in intact Onlays (N=25).

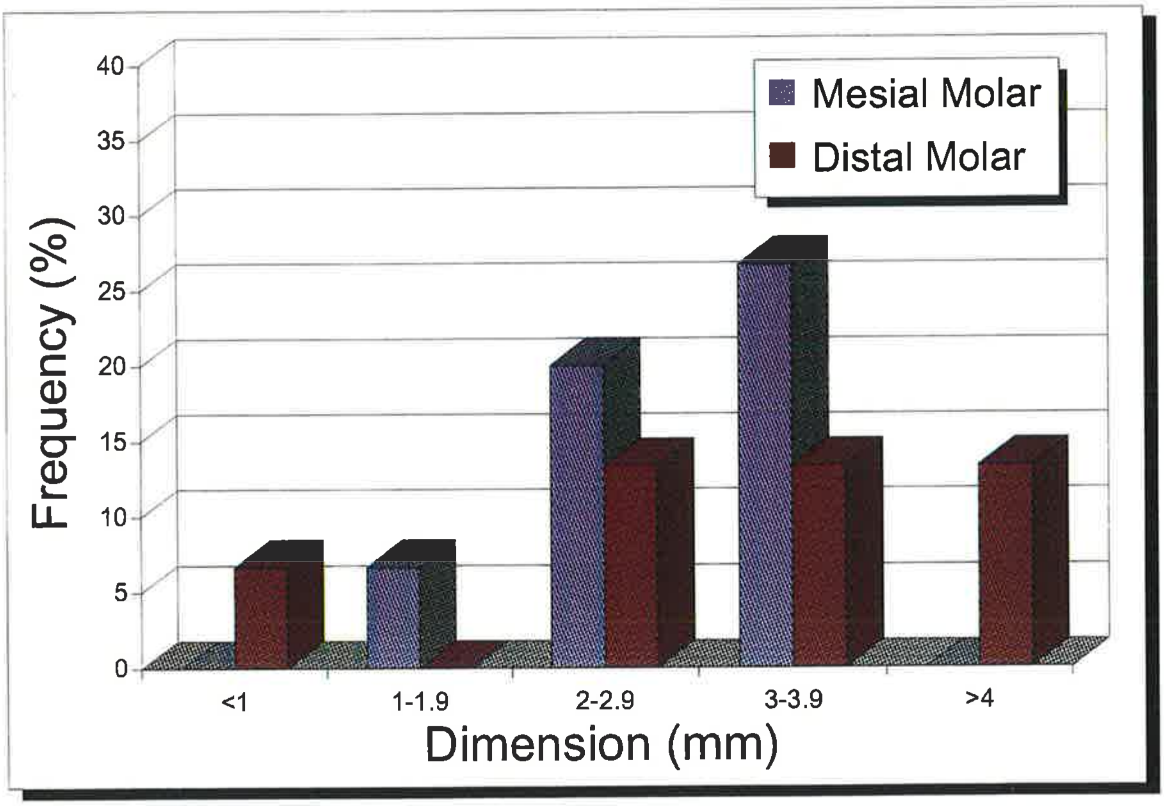


Figure 8b - Height of axial wall in mesial and distal of molar teeth in failed Onlays (N=15).

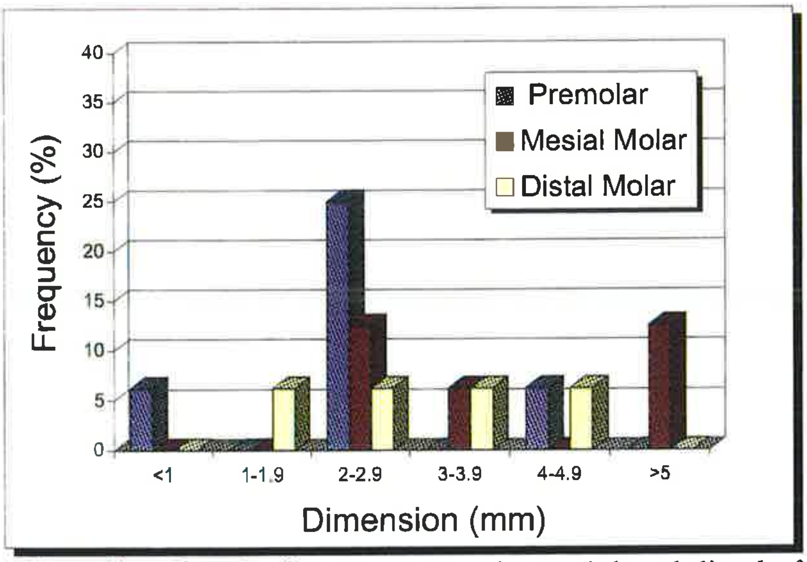


Figure 9a - Depth of occlusal floor in mesial and distal of molar and premolar teeth in intact Shell Crowns without metal Reinforcement (N=15).

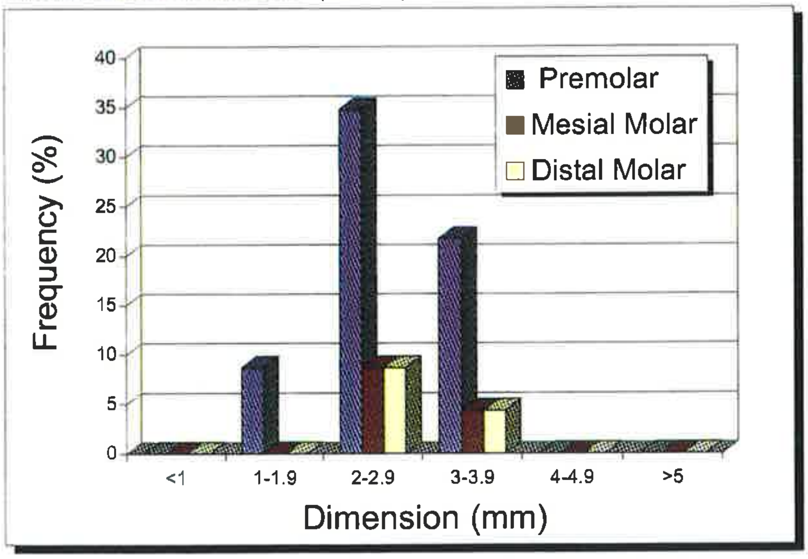


Figure 9b - Depth of occlusal floor in mesial and distal of molar and premolar teeth in intact Shell Crowns with metal Reinforcement (N=21).

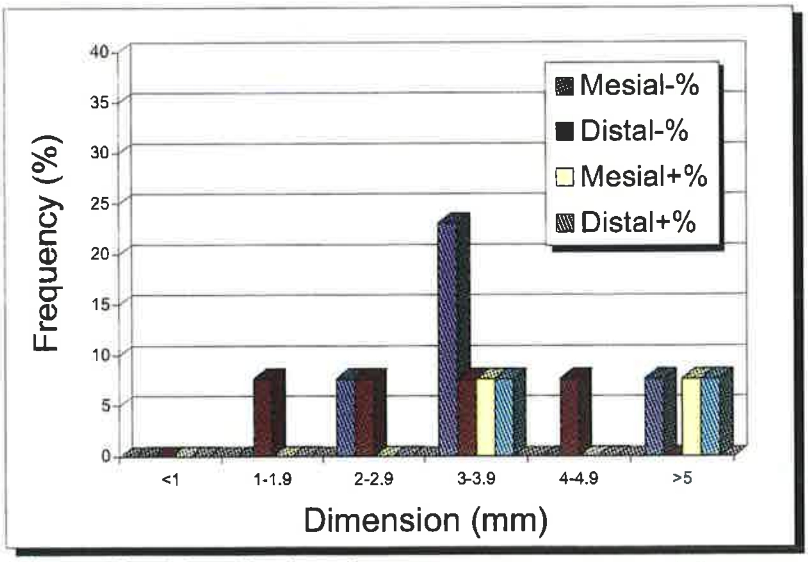


Figure 9c - Depth of occlusal floor from Central fissure in posterior teeth in failed shell Crowns with (N=4) and without (N=9) metal Reinforcement.

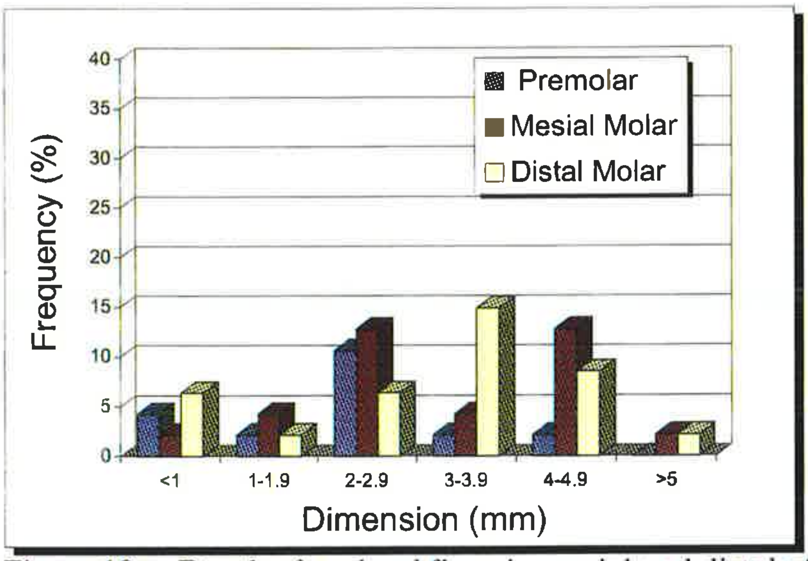


Figure 10a - Depth of occlusal floor in mesial and distal of molar and premolar teeth in intact Onlays without metal Reinforcement (N=47).

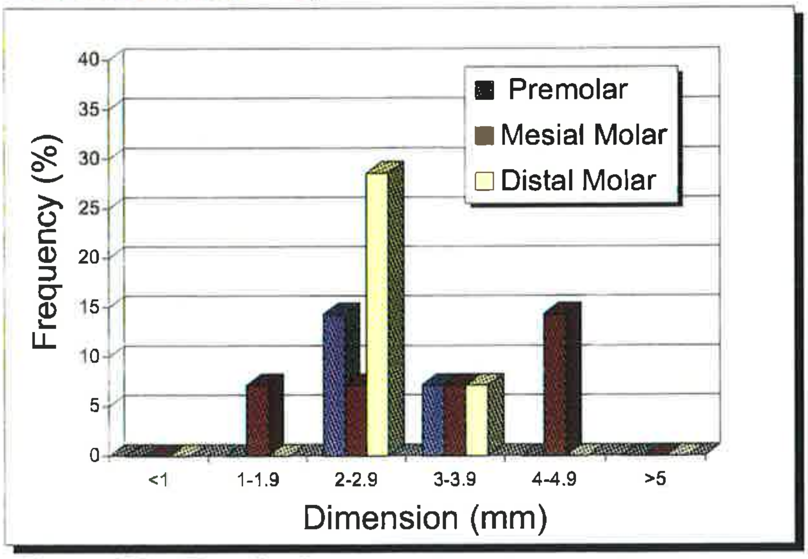


Figure 10b - Depth of occlusal floor in mesial and distal of molar and premolar teeth in intact Onlays with metal Reinforcement (N=13).

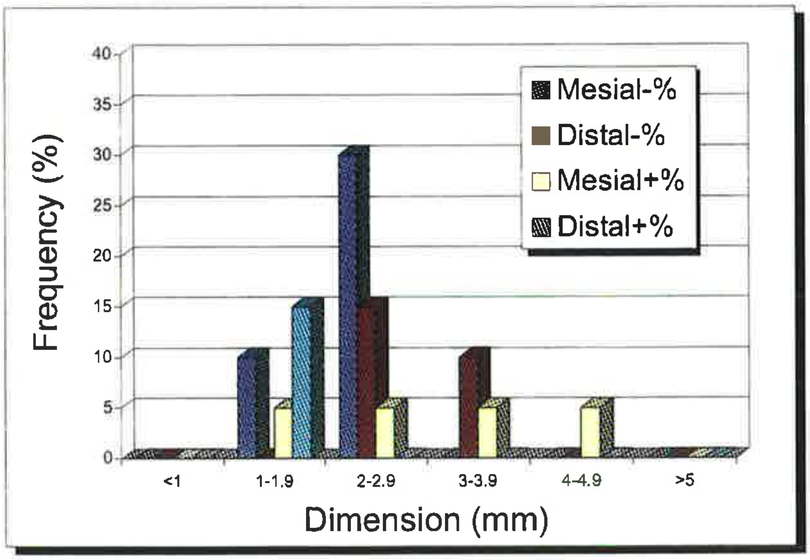


Figure 10c - Depth of occlusal floor from Central fissure in posterior failed Onlays with (N=7) and without (N=13) metal Reinforcement.

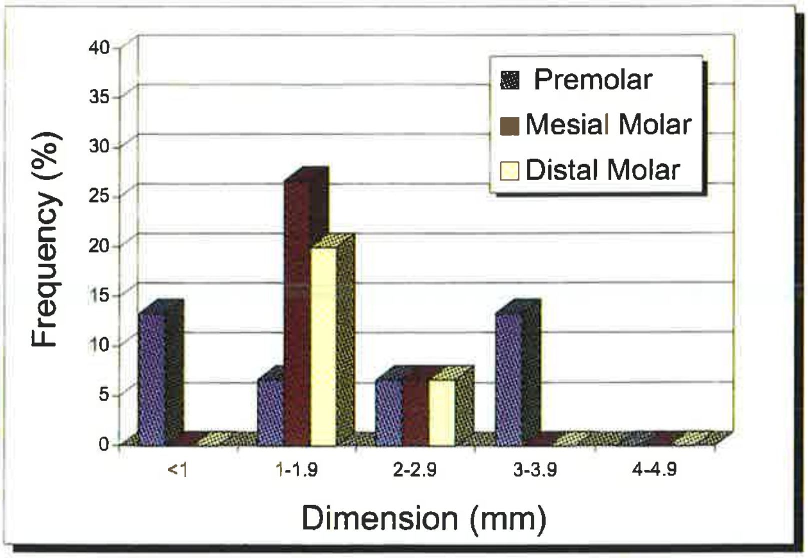


Figure 11a - Cusp reduction in mesial and distal of molar (N=9), and premolar (N=6) teeth in intact Shell Crowns without metal Reinforcement.

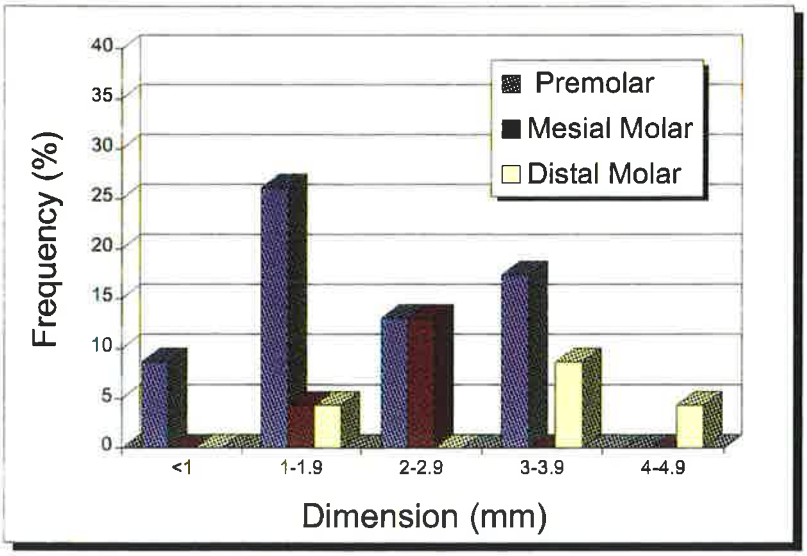


Figure 11b - Cusp reduction in mesial and distal of molar (N=8), and premolar (N=15) teeth in intact Shell Crowns with metal Reinforcement.

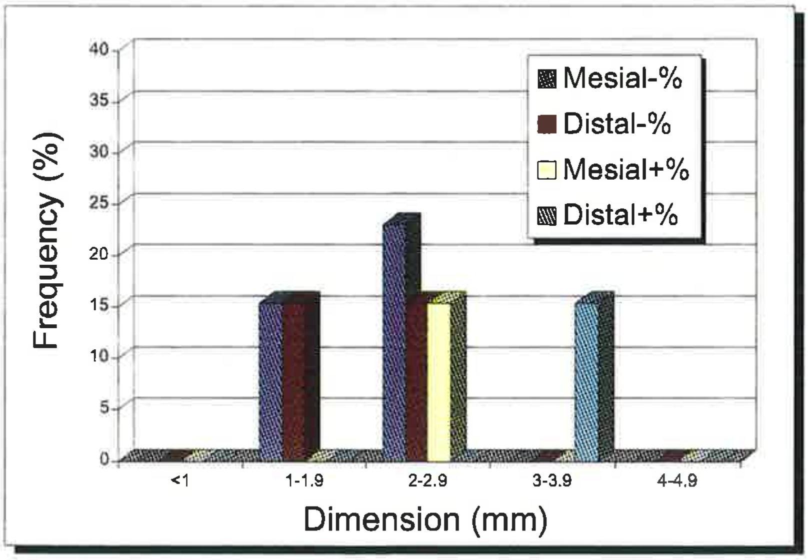


Figure 11c - Cusp reduction in posterior failed Shell Crowns with (N=4), and without (N=9) metal Reinforcement.

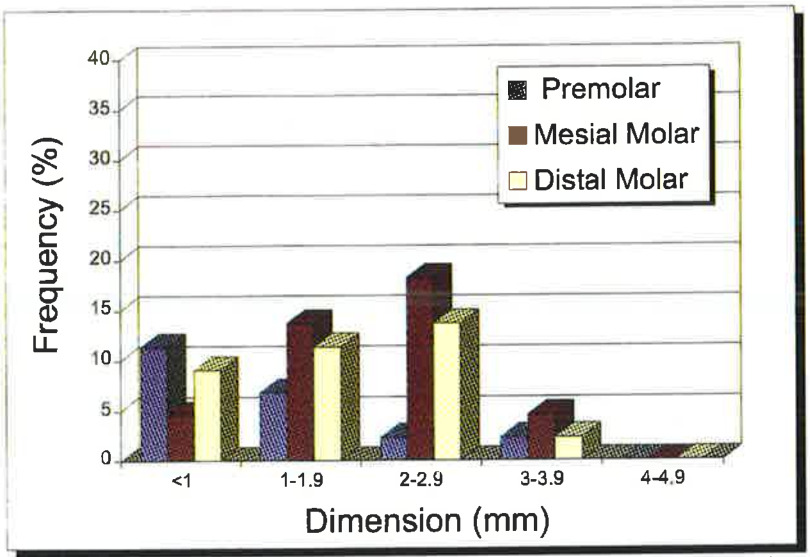


Figure 12a - Cusp reduction in mesial and distal of molar (N=34), and premolar (N=10) teeth in intact Onlays without metal Reinforcement

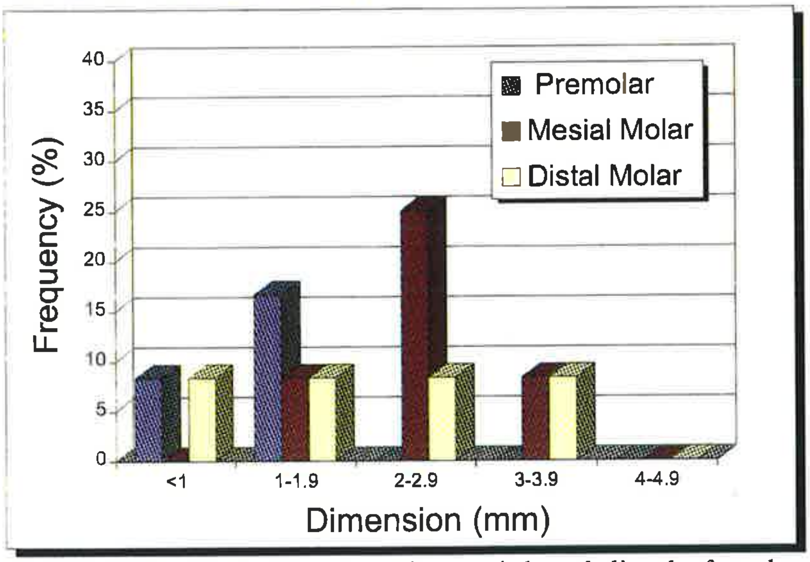


Figure 12b - Cusp reduction in mesial and distal of molar (N=9), and premolar (N=3) teeth in intact Onlays with metal Reinforcement.

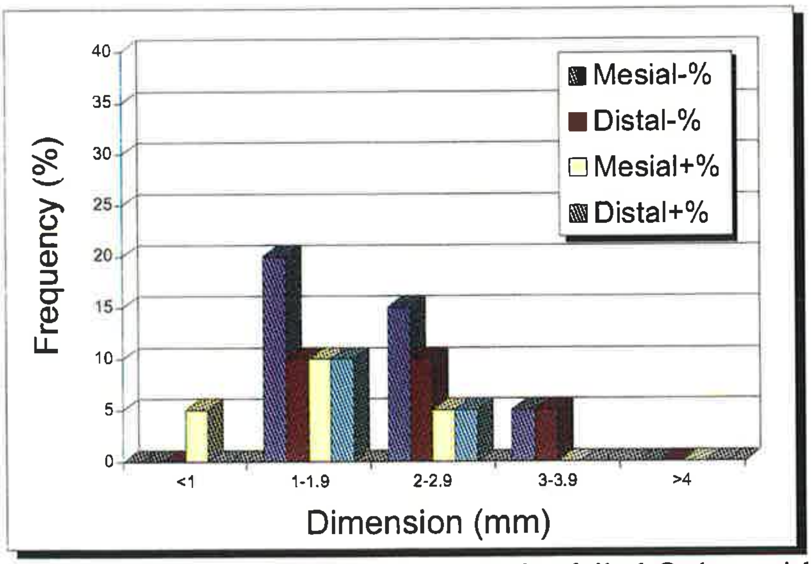


Figure 12c - Cusp reduction in posterior failed Onlays with (N=7), and without (N=13) metal Reinforcement.

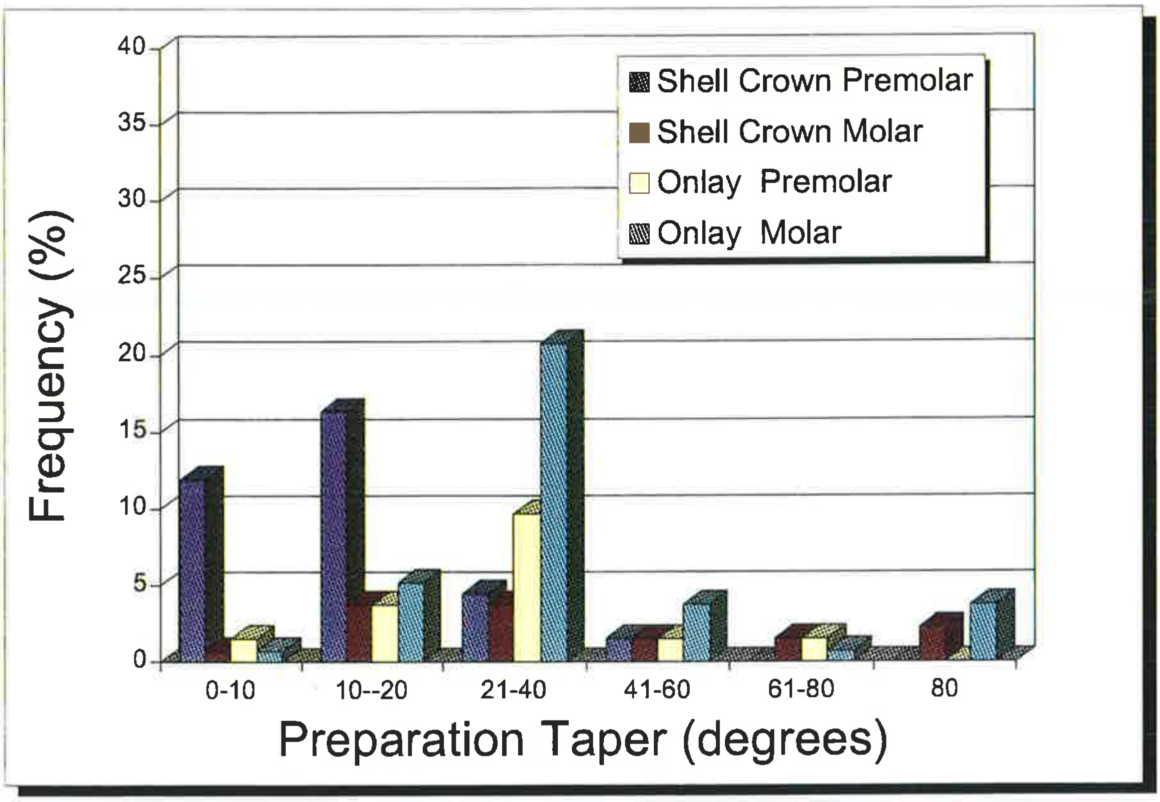


Figure 13a - Preparation taper in molar and premolar teeth in intact Shell Crowns (N=64) and Onlays (N=71).

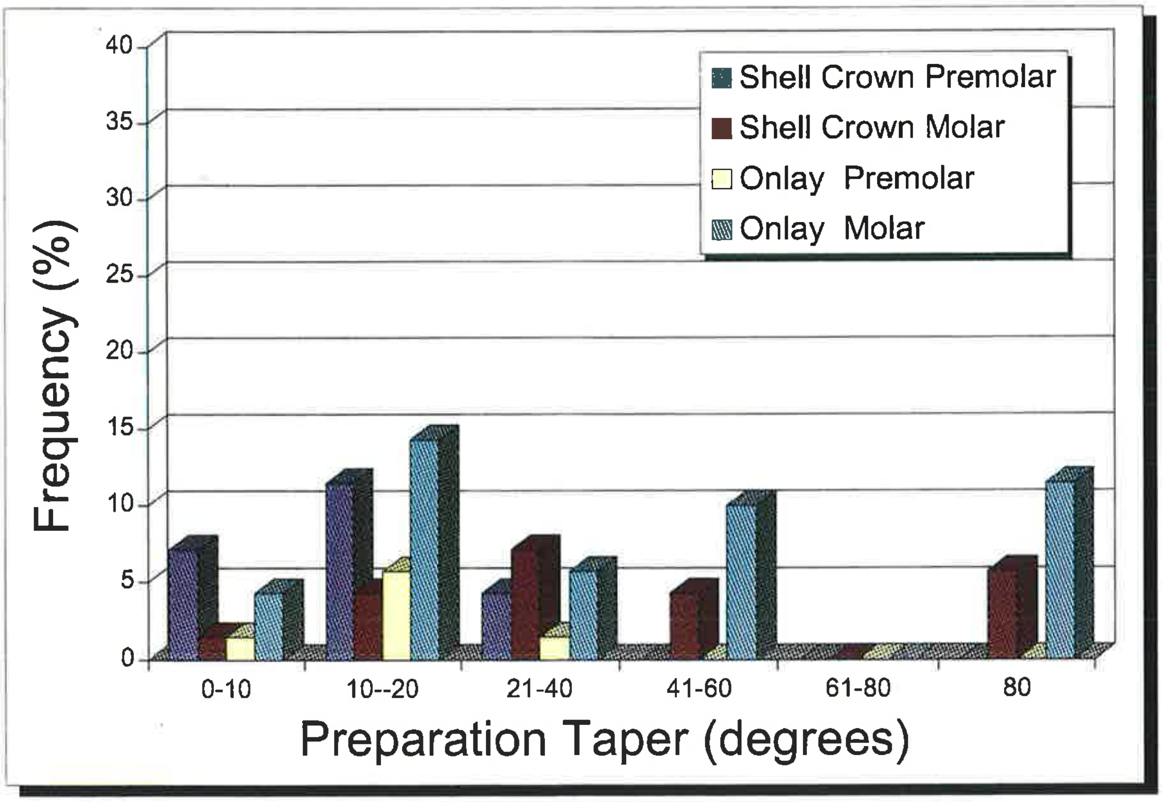


Figure 13b - Preparation taper in molar and premolar teeth in Failed Shell Crowns (N=32) and Onlays (N=38).

5.1.6 Discussion

Resin-bonded posterior porcelain restorations are relatively new to the dental profession. The criteria for tooth preparation for these restorations were based initially on those for traditional cast-metal restorations. These criteria have been changed over time to more closely match the fabrication and handling characteristics and physical properties of dental porcelains. Minimum cavity wall divergence is recommended for cast-metal restorations, to provide maximum retention. However, for bonded-porcelain restorations, retention depends largely on an effective bond to tooth structure. Therefore, slightly larger preparation tapers can be recommended to reduce friction of the fragile porcelain restoration with the cavity walls during its placement, and to provide a bulkier restoration, which is consequently stronger (Roulet and Herder 1991, Ubassy 1992, Broderson 1994). In most of the literature, the recommended preparation designs for resin-bonded porcelain restorations are appropriate for previously-unprepared or minimally carious teeth. However, these designs might not be applicable for the replacement of existing amalgam restorations or for the restoration of carious or fractured teeth. The results of the present study revealed some divergence in practices from recommended preparation designs.

For the dies of the prepared teeth, all cavosurface margins were smoothly curved and no sharp internal line angles were found. This is a requirement for porcelain strength, since sharp angles act as stress concentration areas, and confirms changes in the criteria for the retention of cast restoration preparations (Garber and Goldstein 1994b).

Although marginal bevels are not recommended for all-porcelain restorations (Garber and Goldstein 1994b, Banks 1990), in the present study 7% of shell crown, and 12% of onlay preparations had what appeared to be small bevelled gingival margins (Tables 17a and 18a). It seems that this type of preparation design, which was present with some proximal boxes, was not used deliberately by the operators for the resin-bonded porcelain restorations, and may have been present from previous cavity preparations for amalgam restorations. Higher failure rates were found in restorations with bevelled gingival margins (Tables 17b and 18b). Very thin edges of porcelain can be easily fractured by handling, or during cementation.

Occlusal slots or boxes were present in relatively few preparations for shell crowns, but in 47% of premolars and 81% of molars for onlay restorations (Figure 2). These occlusal slots were the result of the removal of previous amalgam restorations. However, as most of the shell crowns were fabricated because of tooth discolouration, wear or malocclusion, this explains the lower number of occlusal slots present in such restorations.

Preparation tapers were usually measured internally (at occlusal boxes) for onlays, and externally for shell crowns (Figure 11, Chapter 4). The average isthmus widths of these occlusal boxes ranged between 3.1-4.2 mm (Tables 7a and 8a). When comparing these values to the average intercuspal widths of 4.5-6.8 mm (Tables 5a and 6a), the widths of the occlusal boxes were approximately two-thirds those of the intercuspal widths. This ratio shows that the occlusal boxes were wider than perhaps expected. Very divergent axial walls, often between 21-40° at occlusal boxes were responsible for the large isthmus widths in these areas (Table 19). However, most of the external preparation walls were prepared with less than 20° tapers, mostly seen in shell crown preparations (Table 19), which accords with recommended preparation tapers (Fuzzi et al. 1989, Banks 1990, Roulet and Herder 1991, Malament and Grossman 1992).

While near parallel preparation tapers are recommended for the retention of indirect conventional cast-metal restorations, more divergent preparations are favoured for resin-bonded porcelain restorations. Larger preparation tapers not only reduce the friction of restorations with the cavity walls during their try-in, but also produce bulkier restorations, which are stronger (Freidlander et al. 1990, Munoz et al. 1990, Doyle et al. 1990). In the present study, smaller preparation tapers of 10-20° were found with the fractured restorations (Table 20), while tapers were mostly between 21-40° (Table 19) for the intact restorations. Smaller preparation tapers may be one of the reasons for restoration fracture in this study, because of reduced restoration bulk. Larger preparation taper (21-40°), especially in molar teeth where access is more difficult, does not seem to compromise restoration retention, and may be the most practical preparation design for replacing previous amalgam restorations.

With an effective bond of porcelain restorations to tooth structure established by resin composite adhesives, there is no need to cut occlusal steps or proximal boxes. After discussions with the operators, it was found that the few shallow retention boxes present in the preparations (Tables 17a and 18a) were usually left after amalgam removal, at an early stage of the operators' experience with resin-bonded porcelain restorations. These boxes were not seen in the more recent preparations. These boxes would have had a minimal effect in increasing the strength of the restorations. In addition, any such boxes and any undercuts present in the dies were heavily blocked out before the porcelain restorations were fabricated.

Bonding to enamel is always emphasised in order to produce strong and durable bonds between porcelain restorations and tooth structure (Tseng et al. 1992, Swift et al. 1995).

In the present study, 9% of shell crown and 4.7% of onlay margins were in dentine (Tables 17a and 18a). Since none of these restorations failed, it seems that an adequate bond was produced with the dentine bonding adhesives used. Newer dentine bonding systems are reported as being able to overcome the initial polymerisation contraction of resin composites, and to provide early strong bonds (Øilo et al. 1990, Swift et al. 1995).

Proximal boxes of varying sizes were present for 26% of shell crown, and for 44% of onlay preparations (Tables 17a and 18a). The number of MOD cavities was much higher for onlays than for shell crowns, as a result of the removal of existing amalgam restorations. Large proximal boxes resulted in large internal preparation tapers, mostly seen for the MOD onlay restorations. Proximal box widths were larger in distal than in mesial sites, which might be because of the larger contact areas found distally, or because of the difficulty of access for distal preparations. Similar findings were reported by Stassinakis et al. (1996).

To reinforce the restorations, a metal substructure was incorporated in 57% of shell crown, and in 19% of onlay restorations (Tables 17a and 18a). The amount of tooth reduction present for restorations with and without metal reinforcement was not markedly different (Tables 13a-16c). The average occlusal reduction at the central fossae was between 2.1-3.9 mm for both intact shell crowns and intact onlays (Tables 13a-14c), which was slightly more than the 1.5-2.0 mm recommended in the literature (Roulet and Herder 1991, Ellison et al. 1992, Garber and Goldstein 1994b, Cavel et al. 1995). This increased reduction resulted from the occlusal slots present in most of the dies, specially for the onlay preparations (Tables 17a and 18a). In several instances, molar preparations were extended into the pulp chambers of root canal filled teeth (Figure 1).

The average working-cusp reduction was between 1.2-2.9 mm (Tables 15a-16b) for intact shell crowns and onlays, with and without metal reinforcement. Again, it seems that no extra reduction was required for those restorations with a metal substructure. Although the average cusp reductions were almost within the recommended range (1.5-2.0 mm), thicknesses less than 1.0 mm and more than 4.0 mm were also found for intact restorations. In contrast to the study by Milleding et al. (1995), in which fractures occurred in thinner restorations, the results of this study showed that the fractured restorations were slightly thicker than the intact restorations at the central fossae and working cusps. Therefore, it seems that porcelain thickness is not the only factor determining the survival of posterior resin-bonded porcelain restorations. Thickness might be an important clinical factor for fracture of restorations during the early stages. However, other factors such as porcelain voids and flaws (Øilo 1988, Messer et al. 1991), moisture (Kelly et al. 1989, Messer et al. 1991, Malament and Grossman 1992) and the deterioration of adhesive bonds are also responsible for fracture of the restorations over the longer term.

5.1.7 Conclusions and Recommendations

For the 103 posterior porcelain shell crown and onlay preparation designs examined in this study, it was found that:

1) Proximal boxes and occlusal steps or slots were present more frequently in onlay than in shell crown preparations. The boxes were usually larger on the distal than on the more accessible mesial preparation sites, and resulted from the removal of existing amalgam restorations.

2) The average widths of the isthmuses were approximately two-thirds of the intercuspal site widths, and wider than expected because the internal tapers or convergency angles were frequently greater than 20°. The usual amount of preparation taper was greater than the recommendations of 6-15° made for porcelain restorations, but taper could not be related to subsequent restoration fracture.

3) There were vide variations in the amounts of preparation reduction in the central fossae and over the working cusps, ranging from 0.5-6.0 mm. However, although the average occlusal thickness of porcelain measured centrally was slightly more than the minimum recommendation of 1.5-2.0 mm, the average thickness over the working-cusps was generally within the recommended range.

4) Essentially, the average preparation dimensions for both the intact and the fractured restoration groups were very similar, and there were wide variations present in the range of measurements recorded for both groups.

5) Preparation dimensions were similar in restorations with and without metal reinforcement.

Within the limitations of this study, it was concluded that factors other than preparation design would also seem to be important in determining the survival of posterior resin-bonded porcelain restorations. The results of the present study showed that the usual criteria stated for the preparation of resin-bonded porcelain restorations can be modified according to the clinical situation, provided that an adequate adhesive bond is obtained between the porcelain restoration and tooth structure, and a minimum bulk of porcelain is present occlusally, generally within the range of 1.0- 2.0 mm. There is more flexibility in preparation designs for bonded-porcelain than for traditional cast restorations.

5.2 SECTION TWO: RESTORATION FAILURES

5.2.1 Introduction

In this section, the in vivo investigation of restoration failures is presented in two parts:

5.2.2 Sample population (including gender, age range, restoration distribution in maxilla and mandible, restoration distribution for operator 1 and 2, and the reasons for restoration placement and replacement),

5.2.3 Restoration failures (failure types and failure reasons).

Tables of the results for restoration failures are shown in Appendix IV.

5.2.2 Sample Population

5.2.2a Gender

The patient sample used in this study was drawn entirely from a specialist private dental practice in which two prosthodontists worked. There were 222 patients involved in the study. Of this population, 140 (63%) were female, and 82 (37%) were male (Table 1). The number of patients seen by each dental operator is shown in Table 2a. For each operator, most of the patients were aged from 31-50 years. There were no significant differences present in gender distribution, either between the age groups or the operators ($P>0.25$).

5.2.2b Age Range

Since age is relative, the considered age for each patient in this study was the age of the patient at the time the resin-bonded porcelain restorations were placed. The age range was classified into five groups. Table 1 shows the age cohorts, and numbers and percentages of male and female patients in each cohort. Most of the patient population belonged to the age range of 31-50 years for both male and female patients. The lowest number of patients was found in the age cohort of 10-20 years. The age distribution of patients ranged from a minimum of 10 years to a maximum of 69 years. Table 2b presents the number of restorations in each age cohort. The highest number of restorations were placed in the age group of 41-50 years. The age group of 21-30 years had the lowest number of restorations.

5.2.2c Distribution of Restorations

In this section, the distribution of restorations is presented as:

5.2.2c1: Restoration distribution in male and female patients,

5.2.2c2: Restoration distribution in the maxilla and mandible,

5.2.2c3: Restoration distribution with and without metal reinforcement,

5.2.2c4: Restoration distribution by operators.

5.2.2c1 Restoration Distribution in Male and Female Patients

Table 3 shows the numbers of each type of restoration placed in male and female patients. The number of restorations placed in males was 210 and in females 326. There was a significant difference present in the distribution of the restoration types between males and females ($p = 0.001$).

5.2.2c2 Restoration Distribution in Maxilla and Mandible

The distribution of the restorations in the anterior and posterior regions of the maxilla and mandible is presented in Table 4. The number of restorations placed in the maxillary arch (362) was considerably higher than that placed in the mandible (174). Most of the veneers, shell crowns, fixed-fixed and cantilever bridges were placed in the anterior region of the maxilla. This showed a priority indication for resin-bonded porcelain restorations for aesthetic reasons. Onlays were almost totally placed in the posterior region. Four onlays placed in the anterior region, were constructed on canine teeth to restore tooth wear. In the mandible, the total number of restorations placed in the posterior region (113) was almost twice that placed in the anterior region (61). Shell crowns and onlays were the two dominant restorations constructed for the posterior region of the mandible.

5.2.2c3 Restoration Distribution With and Without Metal Reinforcement

The total number of restorations placed in the practice is shown in Table 5. There were 536 restorations of different types (labial veneers with and without incisal coverage, shell crowns, onlays, inlays, porcelain chips, fixed-fixed and cantilever bridges) involved in this study. The highest numbers of restorations were shell crowns (43% of total restoration population), and the lowest were porcelain chips (3%) and inlays (1.6%). The other restorations in order of numbers were onlays followed by veneers, cantilever bridges, veneers with incisal coverage, and fixed-fixed bridges. Table 5 also shows the percentage of restorations with and without metal reinforcement. Most of the shell crowns, onlays and inlays were without metal reinforcement. All bridges had metal substructures except for one cantilever bridge. Most of the retainers (65%) for the bridges were shell crowns (Table 6).

5.2.2c4 Restoration Distribution by Operators

Tables 7 and 8 represent the distribution of restorations in the anterior and posterior regions of the maxilla and mandible for operators 1 and 2. The total number of restorations placed by operator 1 was approximately 1.5 times those placed by operator 2. Again, the number of restorations placed in the anterior region of the maxilla was higher than those placed in the same area of the mandible for both operators. In the mandible, most restorations were placed in the posterior region by both operators. The numbers of shell crowns and onlays with and without metal reinforcement are also presented in Tables 7 and 8. Most of the shell crowns and onlays placed by the operators were without metal reinforcement. Restorations with metal substructures were often made for the posterior teeth. All bridges had metal reinforcement except for one cantilever bridge. This bridge was one of the first restorations placed by operator 2. It was the technician's mistake to make it without a metal substructure. The bridge was lost to follow up at an early stage, and was excluded from the survival analysis.

5.2.2d Reasons for Restoration Placement

This section is subdivided into two sections:

5.2.2d1 Tooth-related reasons,

5.2.2d2 Restoration-related reasons.

5.2.2d1 Tooth-Related Reasons

Any primary problem with a tooth which led to the placement of a resin-bonded porcelain restoration, was considered as a 'tooth-related reason'. Table 9a shows the tooth problems in male and female patients which led to the construction of single or bridge, resin-bonded porcelain restorations. 'Abutment' and 'missing' teeth refer to reasons for placement of a resin-bonded porcelain bridge. Missing teeth represent the number of pontics. There was a significant difference present in the distribution of the reasons between males and females ($p < 0.001$). In female patients, more aesthetic reasons such as discolouration and tooth missing were the dominant reasons for fabrication of relatively more restorations. In male patients, however, the dominant reasons were tooth wear and malocclusion.

5.2.2d2 Previous Restoration-Related Reasons

Any problem relating to a previous existing restoration of any type, which led to the construction of a resin-bonded porcelain restoration, was considered as a 'restoration-related reason' (Table 10a). Again, a significantly different distribution was present ($p<0.001$). In this category also, the more aesthetic problems such as discolouration and wear of previous restorations were the reasons for relatively more restoration placements in female patients. In male patients, the problems with previous restorations which led to the fabrication of a resin-bonded porcelain restoration were considerably less than those in female patients, but included restoration fractures. Mercury scare from amalgam restorations was apparently a worry in a few female patients only (13 restorations).

The reasons leading to the placement of each type of restoration are presented in Tables 9b and 10b. Fractures of teeth and previous restorations were dominant reasons for the placement of shell crown and onlay restorations. Discolouration of teeth and previous restorations were common factors for the placement of shell crown and veneer restorations. Tooth wear and malocclusion were found to be more important reasons to fabricate a veneer with incisal coverage, onlay and shell crown restorations.

5.2.3 Restoration Failures

In this section information about failure types and failure reasons for individual restorations are presented as:

5.2.3a: Failure types for different restorations,

5.2.3b: Failure types for different age groups,

5.2.3c: Failure types for operators,

5.2.3d: Failure types for bruxer and nonbruxer patients,

5.2.3e: Failure types with different bases,

5.2.3f: Failure types with different adhesive cements,

5.2.3g: Failure reasons and treatments after failures.

In some cases there were no reasons mentioned for failures in the patients' casenotes. Therefore, some assumptions were made in these cases according to either other information in the casenotes or after discussions with the operators. The bridges, irrespective of the number of units, were considered as one restoration. Therefore, the failure type was presented as one failure for the whole bridge and not as failures of individual components of the bridge.

To differentiate between different failure modes, the following descriptions were used:

- 'Debonding' refers to an adhesive failure caused by breakdown of the luting cement,
- 'Bulk fracture' is a large catastrophic failure occurring through the body of the restoration,

- 'Chip fracture' is a small fracture of a superficial layer of porcelain of the restoration which is not catastrophic,
- 'Connector fracture' is separation of the bridge components at a connector,
- 'Colour mismatch' is the inability to match the restoration colour with the colour of the existing teeth,
- 'Pulpitis' is any irreversible pulpal change or persistent post-operative sensitivity which needs treatment,
- 'Secondary caries' is recurrent caries under the restoration or at the restoration margins (there were no instances recorded),
- 'Microcracks' are fractures in the body of the porcelain restorations which do not cause any bulk or chip fractures. The restorations are still intact and there is no need for any special treatment. Microcracks were considered as true failures since they were fractures of the porcelain material,
- 'Apparent failure' refers to any failure occurring from extrinsic factors, rather than directly from material or restoration problems. This was separated from 'true failures' mentioned above which occurred because of problems inherent in the restorations. Apparent failures were caused by eg. external acute trauma, a weakened tooth which fractured after root canal filling, or tooth extraction because of root resorption or failed root canal therapy.

5.2.3.a Failure Types for Different Restorations

Table 11 displays the number and percentage of failures for each restoration type. The percentages presented in the last column of the table are the proportions of failures of each type of restorations to the total number of that type of restoration in the study. The total number of failures was 115 (21%) out of 536 restorations (excluding apparent failures). Fixed-fixed bridges showed the highest percentage of failures (70%), mainly from bulk fracture. The rate of failures with cantilever bridges was much lower (20%). Onlay restorations, without and with metal reinforcement, were the next highest type of failed restoration (37% and 32%, respectively), (Table 11). Bulk fracture was the most common failure mode in both subgroups of onlays, followed by pulpitis and chip fracture. Failures of shell crowns, with and without a metal substructure, were slightly lower (15% and 22%, respectively). Bulk fracture was reported in 16 of the shell crowns without a metal substructure, but in none of the crowns with metal reinforcement. Again, pulpitis followed by chip fracture were other common failures. Veneers without incisal coverage showed more failures (14%) than those with incisal coverage (2%). Bulk fracture was the most common failure mode in the veneer restorations.

The second last row of Table 11 shows the percentages of each failure type as a proportion of the total number of failures (123). The last row of the table, however, represents the percentages of each failure type as a proportion of the total number of the restorations. Bulk fracture was the predominant failure mode, followed by debonding, pulpitis and chip fracture. Microfractures were not always recorded in the patients' casenotes by the operators. Therefore, the number of restorations with microfractures may be higher than presented in this study. No recurrent caries was reported.

It should be noted here that the number of failures in Table 11 does not necessarily represent the number of failed restorations since, in a few cases, a combination of two failures occurred with the one restoration. For example, with the fixed-fixed bridges, two bridges had a combination of bulk/chip fracture, and bulk fracture/colour mismatch. Similarly, one cantilever bridge showed pulpitis/debonding. One shell crown (without metal reinforcement) had debonding/food impaction. Two onlays failed because of bulk fracture/debonding (without metal), and bulk fracture/colour mismatch (with metal).

Table 12 shows the number of failed restorations for the anterior and posterior regions of the maxilla and mandible. In each row, the percentage of failures relative to the number of that restoration placed in the anterior and posterior regions of the maxilla and mandible are presented in parentheses. Out of 27 fixed-fixed bridges, 17 failed (16 anterior and 1 posterior). With regard to the total number of fixed-fixed bridges in the anterior and posterior regions (Table 4), failures of this restoration were very high. Of the 49 cantilever bridges, eight anterior and one posterior bridge failed. It should be noted that two of the failures in the anterior region were 'apparent', and not directly related to the restoration or material. Bulk fracture and debonding were the most common failure modes for cantilever bridges, while for fixed-fixed bridges bulk fracture through the retainers or connectors were the dominant failure causes (Table 11). No connector fractures were reported for the cantilever bridges. Shell crowns without metal reinforcement showed a higher level of failure than those with metal reinforcement in the posterior area. As can be seen from Table 12, failures of restorations in the mandible were much higher than those in the maxilla.

Retainer designs for the bridges are shown in Table 6, and the number of failed retainers for the bridges in the anterior and posterior regions are presented in Table 13. Veneer retainer designs for both types of bridges showed the highest failures.

5.2.3b Failure Types for Different Age Groups

As mentioned previously in section 5.2.2b, patients were divided into five age groups. Table 14 shows the number of failures for each age group. It also shows the percentage of failures in each age group relative to the number of restorations in that group. Most failures happened after the age of 31 years, with the age cohort of 31-40 years showing the highest failures (36%). The lowest failures were in the age group of 21-30 years (12%). Bulk fracture was common in the age cohorts of 31-40, 41-50, and 51+ years, and pulpitis was only reported by patients in these three groups. Other failure modes were spread across all groups. However, apparent failures were more common in the teenager group (10-20 years).

5.2.3c Failure Types for Operators

Presented in Tables 15 and 16 are the number of failures of restorations placed by the two operators. The rate of failures were 22% and 25% for operator 1 and 2, respectively. Bulk fracture failures did not differ between operators. While debonding and colour mismatch occurred more often in restorations placed by operator 1, pulpitis was reported more often by patients treated by operator 2. Although microfractures were noted in the restorations of operator 1 only, operator 2 might not have reported this problem in the patients' casenotes.

Displayed in the last column of Tables 15 and 16 (in parentheses) are the percentages of failures of each type of restoration relating to the total numbers of that restoration placed by each operator. Fixed-fixed bridges and onlay restorations had the highest failures for both operators. Shell crown and chip restorations placed by operator 1 showed considerably more failures than those placed by operator 2. On the other hand, the failure of cantilever bridges for operator 2 was twice that for operator 1.

5.2.3d Failure Types for Bruxer and Non-bruxer Patients

Because of the possible importance of the effects of parafunctional habits on the longevity of resin-bonded porcelain restorations, the distribution of restorations and their failures in bruxer patients are presented in this section. There were 16 bruxer patients involved (eight male, eight female). Shell crowns and onlays were the more common restorations found in bruxer patients, especially in the posterior region (Table 17a). No fixed-fixed bridges were constructed and only two cantilever bridges were made for these patients. The number of posterior teeth which received bonded porcelain restorations was approximately twice that in the anterior region. Table 17b presents the number and percentages of failures relative to the total number of restorations placed in bruxers (N= 63), and non-bruxers (N= 473), excluding apparent failures. The total percentage of failures in bruxers (30%) was higher than in non-bruxers (22%), which was not significant. The percentages of bulk and chip fractures, and microfractures were relatively higher in bruxers, but not markedly different from those in nonbruxers. Table 17c represents the failure modes of each restoration type in bruxer patients in the anterior and posterior regions. Except for restorations which were specifically constructed for the anterior region (veneers, chip restorations), and one cantilever bridge, all other failures in bruxers occurred in the posterior teeth. Presented in the last row of Table 17c are the percentages of failures of each type of restoration relative to the total number of such restorations constructed in bruxers. Most of the failures occurred with onlays and shell crowns without metal reinforcement, while no failures were found in the same restorations with metal reinforcement. Table 17d represents the average, minimum and maximum longevity of restorations before they failed in bruxers and non-bruxers. The average longevity of restorations was 22.38, and 22.11 months in bruxers and non-bruxers, respectively.

5.2.3e Failure Types with Different Liners/Bases

Three major groups are presented as 'bases' in Tables 18-23. According to the operators, these materials were only used as thin liners over deep axial walls. The prepared teeth which did not receive any bases were named as group 'none' in the tables. Glass ionomer cements were the major base material. Some 'other' types of bases were also variously used to a limited extent by operator 2. Of the total number of teeth involved in this study (565), 61% received no bases, and 36% received glass ionomer cement bases (Table 18). Tables 19 and 20 show the different bases used by the two operators. The number of teeth without bases was approximately twice those with bases, for both operators. While operator 2 used a wider range of different bases, operator 1 recorded the use of glass ionomer cement bases only. Both operators used glass ionomer cement bases in approximately one-third of their restorations.

Failure types with different bases for operators 1 and 2 are shown in Tables 21 and 22, respectively. Teeth with glass ionomer cement bases showed a higher incidence of post-insertion pulpitis for operator 2. Debonding was found more often in teeth without any bases for both operators. The percentage of failed restorations relative to the total numbers of restorations in each group is presented in parentheses in the last row of Tables 21 and 22. For operator 1, the percentages of restoration failures with and without bases were similar (Table 21), while teeth with glass ionomer bases had a higher percentage of failures for operator 2 (Table 22).

Post-operative sensitivity was a common problem reported with resin-bonded porcelain restorations. Displayed in Table 23 are the numbers of cases of short-term post-operative sensitivity with regard to the different bases used in this study. For both operators, post-operative sensitivity was dominantly seen in restorations with glass ionomer cement bases. Table 24 shows the number of cases of short-term post-operative sensitivity, and those which led to intractable pulpitis, for the different restoration types. Out of 52 cases of post-operative sensitivity, 15 became intractable and needed treatment. The percentages of post-operative sensitivity and intractable pulpitis to the total numbers of teeth restored (565) in the study are presented in parentheses in the last column of Table 24. Nine percent and 2.7% of the total teeth restored showed post-operative sensitivity and intractable pulpitis, respectively.

5.2.3f Failure Types with Different Resin Composite Luting Agents

Table 25 shows the different resin composite cements used by the operators. Ultra-Bond was almost totally used by operator 1, whereas operator 2 mainly used Mirage and Insure cements. A wider variety of adhesive cements was used by operator 2 than was used by operator 1. The frequency of cement usage is shown as a percentage of the total number of restorations (536) in the last row of Table 25. Ultra-Bond, Mirage, and Insure were most commonly used by the operators. Failure types associated with the different cements are shown in Table 26. The percentages of failures associated with the different cements are displayed in the last row of the table. The highest failures were recorded for Mirage, followed by Ultra-Bond. Bulk fracture, debonding and pulpitis were common reasons for the failures with both cement types. Restorations cemented with Insure showed the lowest rate of failure (3%).

5.2.3g Failure Reasons and Treatments after Failures

In this section the reasons assumed for failures and the treatments of failed restorations are presented:

5.2.3g1: Debonding,

5.2.3g2: Bulk Fracture,

5.2.3g3: Chip Fracture,

5.2.3g4: Microfractures,

5.2.3g5: Colour Mismatch,

5.2.3g6: Pulpitis,

5.2.3g7: Apparent Failure.

The percentages described here are shown in the last column of Table 11.

It should be noted that the operators did not record the failure reasons in all instances. In these cases some assumptions were made after discussion with the operators and according to the existing facts in the casenotes. For example, if a restoration fractured and the patient was a bruxer, the reason for fracture was assumed to be 'occlusal stress'. Some restorations failed more than once and the operators had to remake them. One option was to remake the restoration with the same original design (eg porcelain onlay replaced by another onlay), or to remake the restoration with a different resin-bonded porcelain design (eg porcelain onlay replaced by a shell crown). Another option was to replace the resin-bonded porcelain restoration with a completely different restoration, such as a gold or a porcelain fused to metal (PFM) crown or bridge. Out of 116 failed restorations, 48 were remade and the rest replaced. Out of the 48 remade resin-bonded porcelain restorations, 11 failed again. Nine of these restorations were remade for the second time, and two rebonded. One restoration failed for a third time and was then replaced with a PFM crown.

5.2.3g1 Debonding

In some cases a combination of debonding and bulk fracture, or pulpitis were reported. Out of 536 restorations, 15 (2.8%) debonded (Table 11). Most of the debondings were assumed to be caused by occlusal stress and poor enamel quantity, followed by poor etching or contamination, and poor enamel quality. In two shell crowns, a combination of occlusal stress and poor enamel quantity probably led to the debondings. Out of 15 debonded restorations, five were remade, five were rebonded, and five were replaced. All restorations which had debonded because of possible poor enamel quantity had to be finally replaced with PFM or gold crowns. One shell crown was remade twice and was finally replaced with a PFM crown.

5.2.3g2 Bulk Fracture

Of the 536 restorations, 56 (10.4%) had bulk fractures (Table 11). The dominant reason for bulk fracture was thought to be occlusal stress (52 cases). Three other cases fractured because of possible poor enamel quantity. In one instance, the restoration had been fabricated on a root canal filled tooth with a cast-post, which resulted in restoration fracture probably because of lack of tooth structure. In 24 cases the operators had to replace the restorations with another type. However, in most instances, the fractured restorations were either remade (24 cases), or they were repaired (8 cases). Of the 24 remade restorations, four refractured and were replaced with PFM or gold crowns. Of the 27 fixed-fixed bridges, there were bulk fractures in 11 instances. They probably fractured due to occlusal stress (10 cases), and poor enamel quantity (one case). Five of these fractured bridges were replaced with PFM bridges. Three were remade as cantilever bridges, where one retainer was involved for the cantilever, and the other retainer was either remade or repaired, or left in place after some adjustment. In the other three cases, the fractured retainers were repaired and the remaining components were left as cantilever bridges. Three fixed-fixed bridges also had connector fractures. One of them was replaced, one was remade as a cantilever bridge, and one was adjusted and left as a cantilever bridge. Out of the 49 original cantilever bridges placed, only three had bulk fractures. Two of these bridges were replaced with PFM bridges, and one was repaired.

5.2.3g3 Chip Fracture

Only 14 (2.6%) of 536 restorations had chip fractures. The most important reason for chip fracture was thought to be occlusal stress (13 cases). In one case, the restoration was chipped because of trauma from a partial denture clasp. Of these chipped restorations, 10 were repaired, and four were adjusted.

5.2.3g4 Microfracture

Six shell crowns and onlays were noted to have microfractures. These were assumed to occur because of occlusal stress or, in one case, because of poor enamel quantity. Only one of the restorations was remade, and the others were left without any special treatment.

5.2.3g5 Colour Mismatch

Five restorations (1%) had colour mismatch problems (two shell crowns, one veneer, one onlay, and one fixed-fixed bridge). The most common reason for colour mismatch was a root canal filled tooth. In one case no reason was recorded by the operator, and it was assumed that there was some difficulty in selecting the correct shade. For the onlay and fixed-fixed bridge, there was a combination of colour mismatch and restoration bulk fracture. Of the five restorations, three were remade (two shell crowns, one fixed-fixed bridge), and two were replaced (one veneer, and one onlay with another material).

5.2.3g6 Pulpitis

As shown previously, out of 536 restorations, 15 (2.7%) were associated with intractable pulpitis which required treatment. Pulpitis was reported with eight shell crowns, six onlays and one cantilever bridge. The reasons for the pulpitis were assumed to be microleakage, occlusal stress, and poor etching or contamination during cementation. Of the onlays, one was remade as a shell crown and the others were remade as onlays again. One onlay required a root canal filling, and was then remade. Of the shell crowns, five were replaced with PFM or gold crowns, and one was remade. Two of the shell crowns required root canal fillings after which the access cavities were repaired. One cantilever bridge had pulpitis and debonding at the same time which was possibly caused by poor etching or contamination during cementation. The bridge was rebonded and the pulpitis disappeared.

5.2.3g7 Apparent Failure

Eight restorations (1.5%) had apparent failures. External acute trauma and tooth fractures (root canal filled and root resorbed) were factors causing the apparent failures. One veneer, four shell crowns, two cantilever bridges and one fixed-fixed bridge had apparent failures. Four of these failed restorations were remade and two were replaced with PFM crowns. Two of the teeth that fractured were replaced by implants.

5.2.4 Examiner Reliability

The percentage agreements for the clinical features of failure type, failure reason, and treatment given ranged from 97 - 100%. Because most of the observations were zero, Kappa values could only be calculated in four instances. The results from Form 2 are shown in Appendix VI.

5.2.5 Limitations of the Study

The accuracy of the information in this study depended upon the accuracy of the information detailed by the operators in the patients' casenotes.

Some information, such as the reasons for restoration failures, required some estimations to be made from the other existing facts in the casenotes, as well as some cross-checking with the operators. The sample population was selected from the operators' files to find the oldest restorations, which led to small sample sizes in some groups such as inlays, porcelain chip veneers, and fixed-fixed bridges. Such restorations were subsequently, either discontinued or seldom placed.

The limited duration of the study also affected the survival analyses results, as 75th and median survival quartiles could not be calculated in some cases (labial veneers with and without incisal coverage, cantilever bridges).

Since the samples were collected from a specialist practice, the results of this study do not represent private general dental practices. In analysing the restorations survivals, attempts were made to follow up the patients, and to update the data. However, this was a problem, since some of the patients either could not be located, or did not wish to attend.

5.3 SECTION THREE: RESTORATION SURVIVALS

5.3.1: Introduction

This section deals with the survival characteristics of restorations of different types. For this study, the restoration survivals were analysed using life table methods (BMDP Statistical Software Program 1L, Dixon 1992). Various analyses included the survival estimates of;

5.3.2.1 all restoration types,

5.3.2.2 veneers with and without incisal coverage,

5.3.2.3 onlays with and without metal reinforcement,

5.3.2.4 shell crowns with and without metal reinforcement,

5.3.2.5 cantilever and fixed-fixed bridges,

5.3.2.6 restorations luted with different resin composite cements,

5.3.2.7 restorations in patients with parafunctional habits,

5.3.2.8 restorations in patients from different age groups, 5.3.2.9 restorations in male and female patients,

5.3.2.10 restorations by arch distribution,

5.3.2.11 restorations placed by different operators.

As mentioned previously, inlay and chip restorations were excluded from the survival analysis because of their small sample sizes. Apparent failures were also excluded from the restorations failures since they occurred due to factors not directly related to the restorations or materials. The number of units involved in the fixed-fixed bridges were three, including one pontic and two retainers. One anterior fixed-fixed bridge comprised six units (two pontics and four abutments), which was excluded from the survival analyses. All of the cantilever bridges were 2-units. The difference between the numbers of restorations and failures in this section, as compared with the numbers presented in section 5.2 (Restorations Failures), is because the inlay and chip restorations, and the apparent failures were excluded from the survival analyses. The 75th survival quartile results were used wherever possible for the survival times. When insufficient failures occurred during the study period, then the survival quartiles could not be provided. Data used for the life table survival estimates are shown in Appendix V.

5.3.2 Restoration Survivals

5.3.2.1 Survival of All Restoration Types

There were sufficient numbers of restorations for porcelain laminate veneers (with and without incisal coverage), onlays, shell crowns, and cantilever bridges to allow statistical analysis (Table 4). There was a statistically significant difference present between the individual restoration types in their survivals (P= 0.001). The survival characteristics of each restoration type and of all restorations are shown in Diagram 1. The estimated 75th survival quartile for all restorations was 58.0± 6.2 months.

Restorations	Number	Failed	Censored	Proportion Censored
Veneers without incisal coverage	64	8	56	0.87
Veneers with incisal coverage	46	1	45	0.97
Onlays	97	32	65	0.67
Shell Crowns	229	40	189	0.82
Fixed-Fixed Bridges	27	16	11	0.40
Cantilever Bridges	49	7	42	0.85

Mantel-Cox Statistic 27.870, P= 0.001

5.3.2.2 Veneers With and Without Incisal Coverage

Diagram 2 shows the survivals of both groups of porcelain laminate veneer restorations. Although veneers with incisal coverage survived better than veneers without incisal coverage, the difference between the two groups was not significant (P= 0.13). No survival quartile results were possible for either type of veneer since the number of failures was too small during the period of study. The survival estimates showed that approximately 96% of veneers with incisal coverage, and 85% of veneers without incisal coverage survived at 84 months.

Restorations	Number	Failed	Censored	Proportion Censored
Veneers without incisal coverage	64	8	56	0.87
Veneers with incisal coverage	46	1	45	0.97

Mantel-Cox Statistic= 2.294, P= 0.13

5.3.2.3 Onlays With and Without Metal Reinforcement

Survival characteristics of onlays are presented in Diagram 3. Since the sample size for the onlays with metal reinforcement was small, failures in this group can have a significant effect on the survival analysis results. No significant difference was found between the survivals of the two groups (P=0.84). The 75th survival quartile was 35.5± 7.6 months for onlays without a metal substructure, and 41.9± 15.8 months for onlays with metal reinforcement.

Restorations	Number	Failed	Censored	Proportion Censored
Onlays without metal reinforcement	78	27	51	0.65
Onlays with metal reinforcement	19	5	14	0.73

Mantel-Cox Statistic= 0.039, P= 0.84

5.3.2.4 Shell Crowns With and Without Metal Reinforcement

In contrast to the onlays, the sample sizes for the shell crowns with and without metal reinforcement were large enough to make valid statistical comparisons. There was no significant difference found between the two groups of shell crowns (P=0.96), as shown in Diagram 4. The 75th survival quartile for shell crowns was 60.4± 13.0 months, and 53.6± 8.3 months, without and with metal reinforcement, respectively.

Restorations	Number	Failed	Censored	Proportion Censored
Shell crowns without metal reinforcement	167	31	136	0.81
Shell crowns without metal reinforcement	62	9	53	0.85

Mantel-Cox Statistic= 0.002, P= 0.96

Diagram 5 presents the survival of shell crowns versus onlays. As mentioned in section 5.2.3a, the failure rate of onlays was higher than that of shell crowns. The results of the survival analysis also showed that shell crown restorations survived better than did onlays. The 75th survival quartiles for shell crowns and onlays were 60.2± 13.7 and 38.0± 9.5 months, respectively. However, the difference between the two restoration types was not statistically significant (P=0.14).

Restorations	Number	Failed	Censored	Proportion Censored
Shell Crowns	229	40	189	0.83
Onlays	97	32	65	0.67

Mantel-Cox Statistic= 2.175, P= 0.14

5.3.2.5 Cantilever and Fixed-Fixed Bridges

The survival characteristics of both types of bridges are presented in Diagram 6. The number of failures of the cantilever bridges during the study was insufficient to calculate the 75th survival quartile. However, the survival estimates showed that approximately 79% survived at least 84 months. For the fixed-fixed bridges, the 75th survival quartile was 20.7± 6.7 months, and the median survival was 56.3± 7.1 months. A significant difference in survival times was present between the two types of bridges (P= 0.02). However, there were relatively few fixed-fixed bridges present.

Restorations	Number	Failed	Censored	Proportion Censored
Cantilever Bridges	49	7	42	0.86
Fixed-Fixed Bridges	27	16	11	0.40

Mantel-Cox Statistic= 5.871, P= 0.02

5.3.2.6 Restorations Luted with Different Resin Composite Cements

In evaluating the survival of the restorations for different adhesive cements, only Mirage, Insure and Ultra-Bond were analysed, because of the small sample sizes for the other cements. As described in section 5.2.3f, Mirage cement had the highest failures followed by Ultra-Bond. The survival analysis in of the restorations in Diagram 7 showed a significant difference between the three groups (P= 0.007). The restorations cemented with Mirage had a 75th survival quartile of 34.9 ± 8.2 months, while for those cemented with Ultra-Bond, the period was 80.6 months. However, insufficient failures for Insure precluded any further analysis.

Cements	Number	Failed	Censored	Proportion Censored
Mirage	102	31	71	0.69
Ultra-Bond	252	47	205	0.81
Insure	62	2	60	0.97

Mantel-Cox Statistic= 9.850, P= 0.007

5.3.2.7 Restorations in Patients with Parafunctional Habits

The results of the present study showed that the survival of restorations placed in patients with parafunctional habits did not differ significantly from those placed in non-bruxer patients (P=0.26), as shown in Diagram 8. Restorations for bruxers had a 75th survival quartile of 58.1 ± 9.0 months, and those for non-bruxers had a 75th survival quartile of 58.5 ± 5.2 months.

Patients Groups	Number	Failed	Censored	Proportion Censored
Non-Bruxers	460	86	374	0.81
Bruxers	54	15	39	0.72

Mantel-Cox Statistic= 1.270, P= 0.26

5.3.2.8 Restorations in Patients from Different Age Groups

Statistically significant differences were found between the five age groups (P= 0.02). The best survival characteristics belonged to age groups 10-20, and 21-30 years (Diagram 9). The numbers of failures in these two groups were too small to allow for 75th survival quartiles. The restorations placed in the patients of the two groups survived well during the period of this study. In the age group of 31-40 years, the 75th survival quartile was 32.2± 10.5 months. In the age groups of 41-50 and 51+ years, the 75th survival quartiles were 65.8± 25.7 and 55.1± 22.0 months, respectively.

Patient Age Groups	Number	Failed	Censored	Proportion Censored
10-20	61	6	55	0.90
21-30	90	8	82	0.91
31-40	105	33	72	0.68
41-50	154	26	128	0.83
51+	104	28	76	0.73

Mantel-Cox Statistic= 11.860, P= 0.02

5.3.2.9 Restorations in Male and Female Patients

The total number of restorations placed in female patients was approximately twice those placed in male patients. Diagram 10 represents the survival characteristics of the restorations placed in male and female patients. A borderline significant difference was found between the survival of the restorations in both groups (P= 0.06). In the female patients, the 75th survival quartile was 47.9± 6.8 months. However, insufficient failures occurred in the male patients to allow statistical analysis.

Patients' Gender	Number	Failed	Censored	Proportional Censored
Male	197	35	162	0.82
Female	317	66	251	0.79

Mantel-Cox Statistic= 3.430, P= 0.06

5.3.2.10 Restorations by Arch Distribution

Because of the limited numbers of some posterior restorations (eg veneers, and bridges), and some anterior restorations (eg onlays), only the survivals of posterior shell crowns and onlays were analysed according to their dental arch distributions. Diagram 11 shows the survival characteristics of shell crown and onlay restorations placed in the posterior teeth of the maxilla and mandible. The survival rates of the restorations was not significantly different(P= 0.11). The maxillary restorations demonstrated superior survival characteristics. The estimated 75th survival quartiles of the restorations were 57.0 months for the maxilla, and 28.0 months for the mandible.

Restorations Sites	Number	Failed	Censored	Proportional Censored
Maxilla Posterior	81	22	59	0.73
Mandible Posterior	107	36	71	0.66

Mantel-Cox Statistic = 2.630, P= 0.11

5.3.2.11 Restorations Placed by Different Operators

A significant difference was found between the survivals of restorations placed by the two operators (P= 0.001, Diagram 12). For the restorations placed by operator 1, the 75th survival quartile was 82.6± 7.3 months, whereas for those placed by operator 2 the 75th survival quartile was at 31.6± 4.5 months.

Operators	Number	Failed	Censored	Proportional Censored
Operator 1	301	53	248	0.82
Operator 2	213	48	165	0.78

Mantel-Cox Statistic= 16.780, P= 0.001

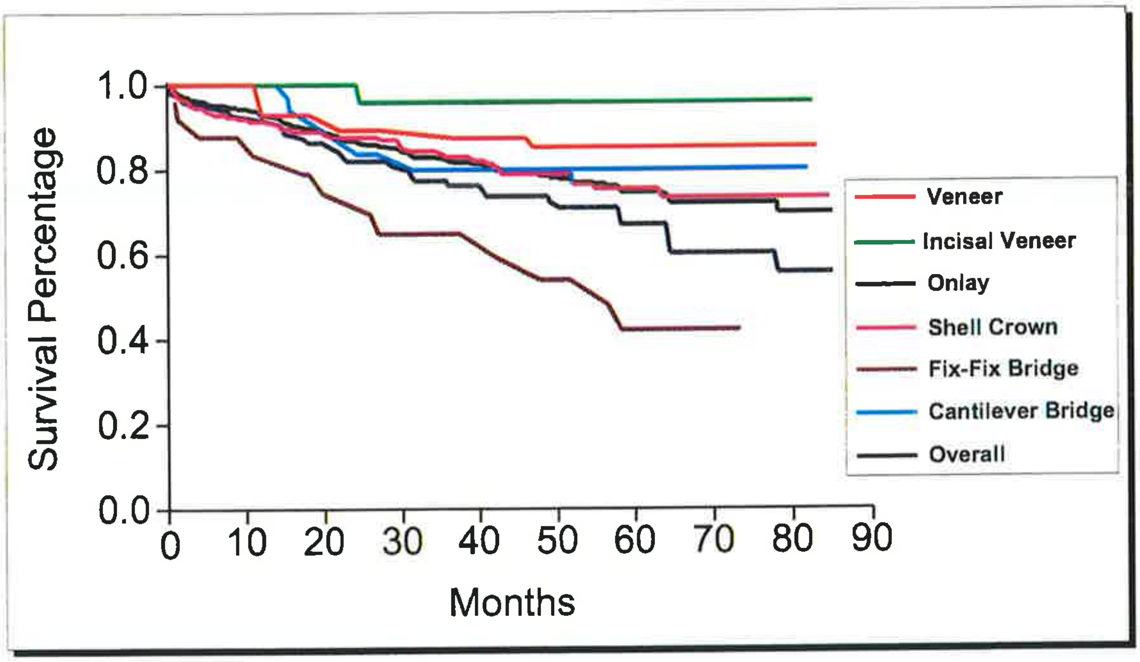


Diagram 1: Survival characteristics of individual restoration types.

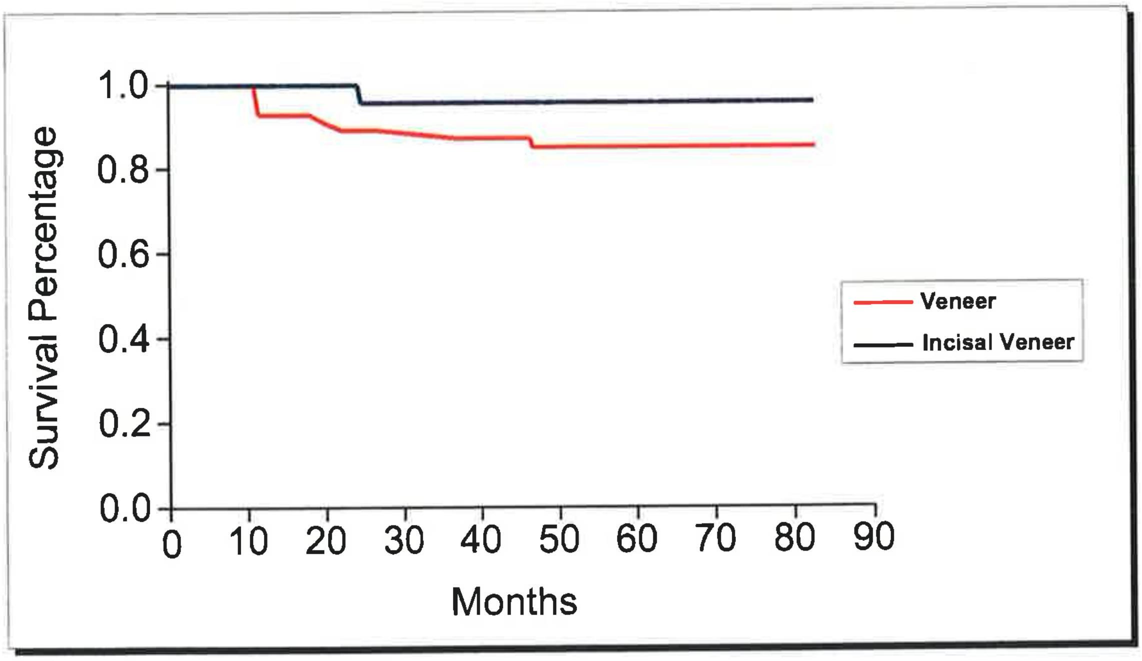


Diagram 2: Survival characteristics of veneers with and without incisal coverage.

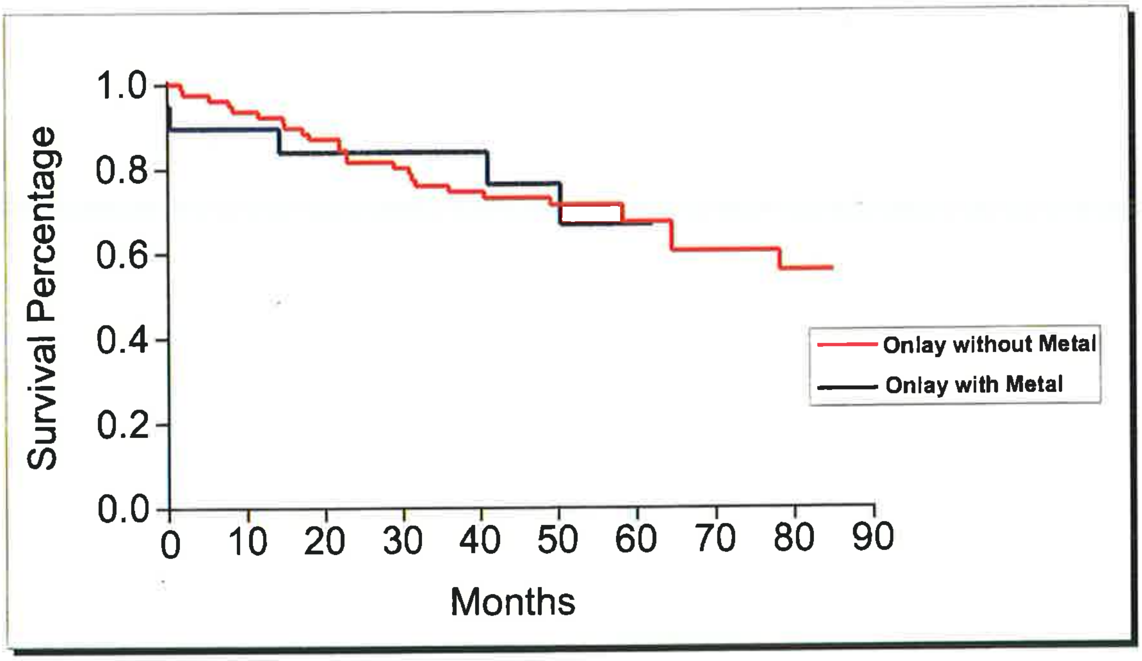


Diagram 3: Survival characteristics of onlays with and without metal reinforcement.

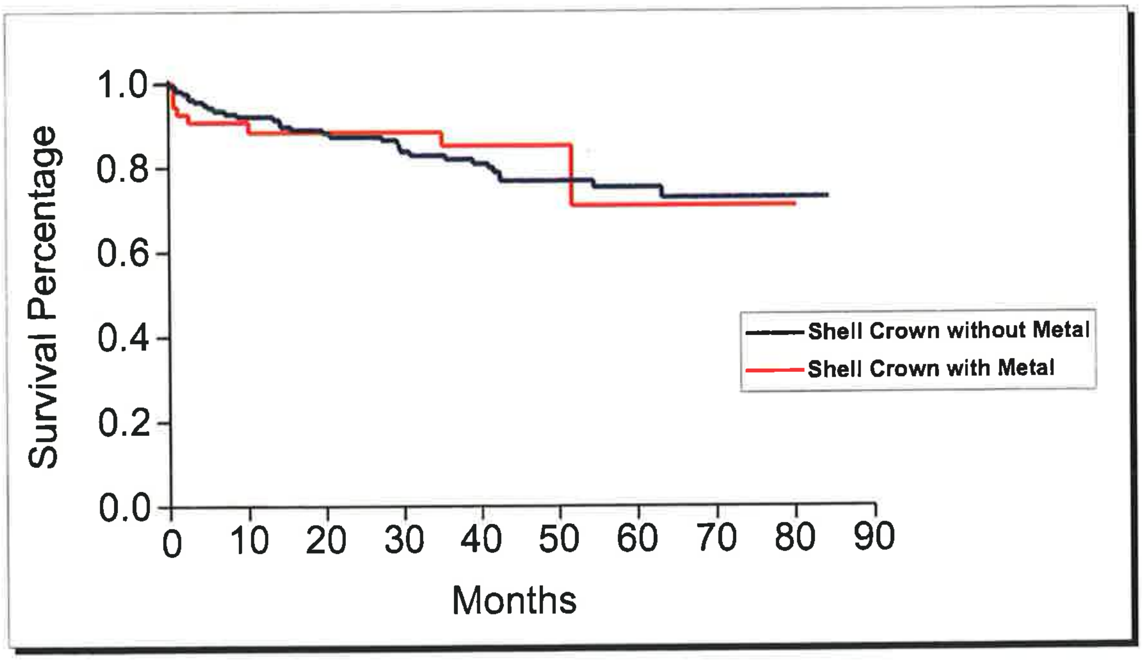


Diagram 4: Survival characteristics of shell crowns with and without metal reinforcement.

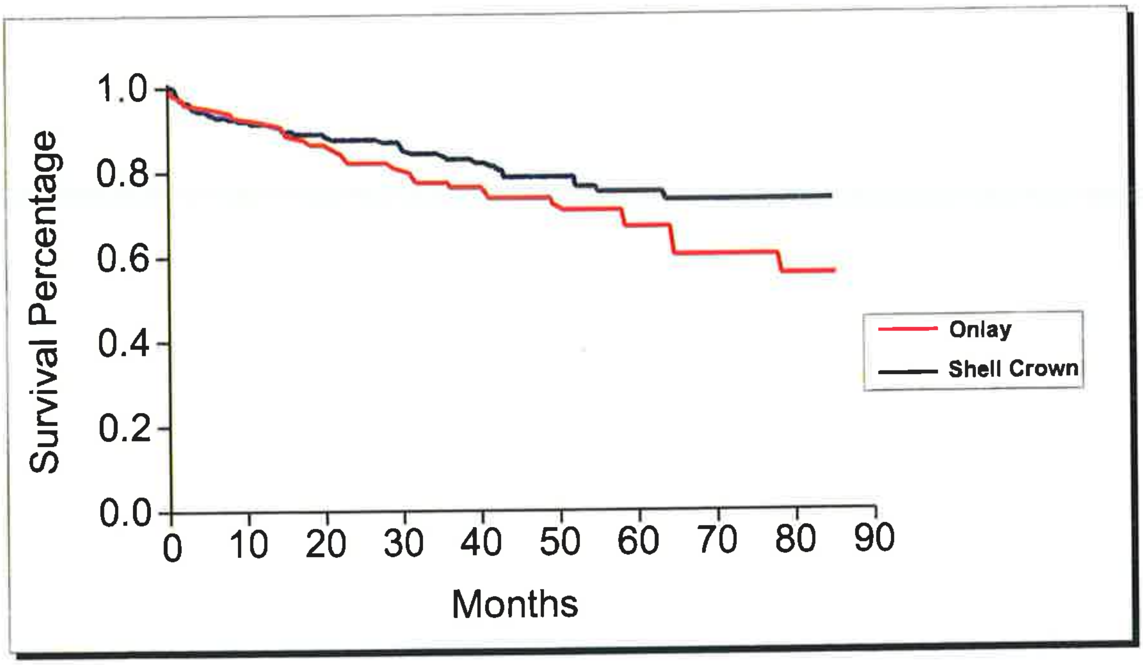


Diagram 5: Survival characteristics of shell crowns and onlays.

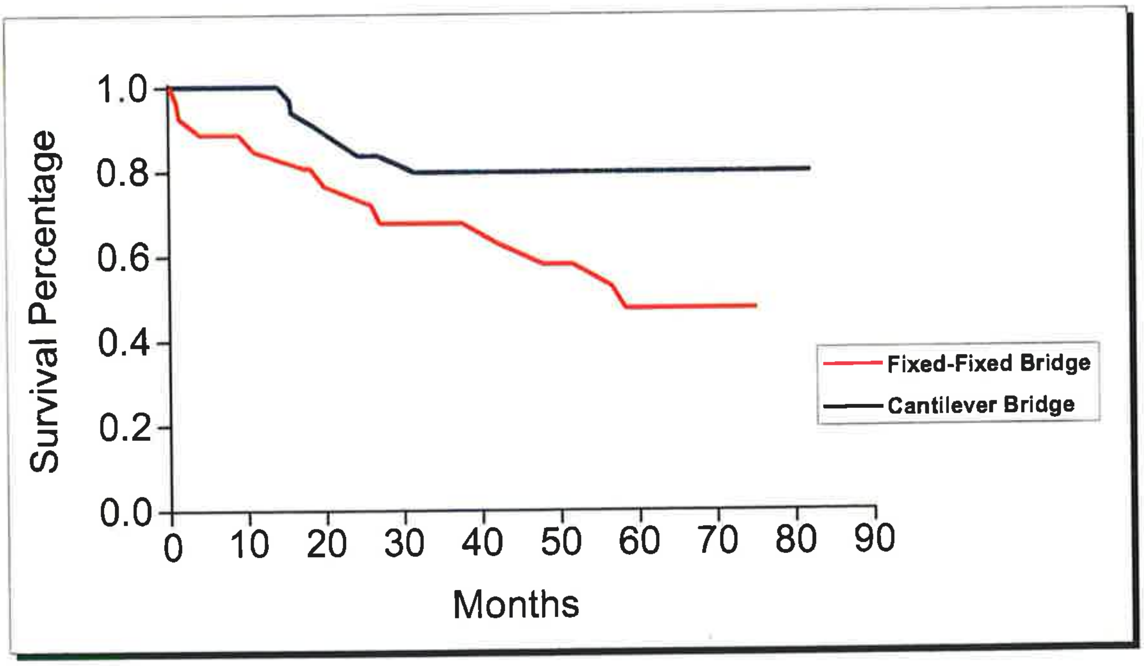


Diagram 6: Survival characteristics of cantilever and fixed-fixed bridges.

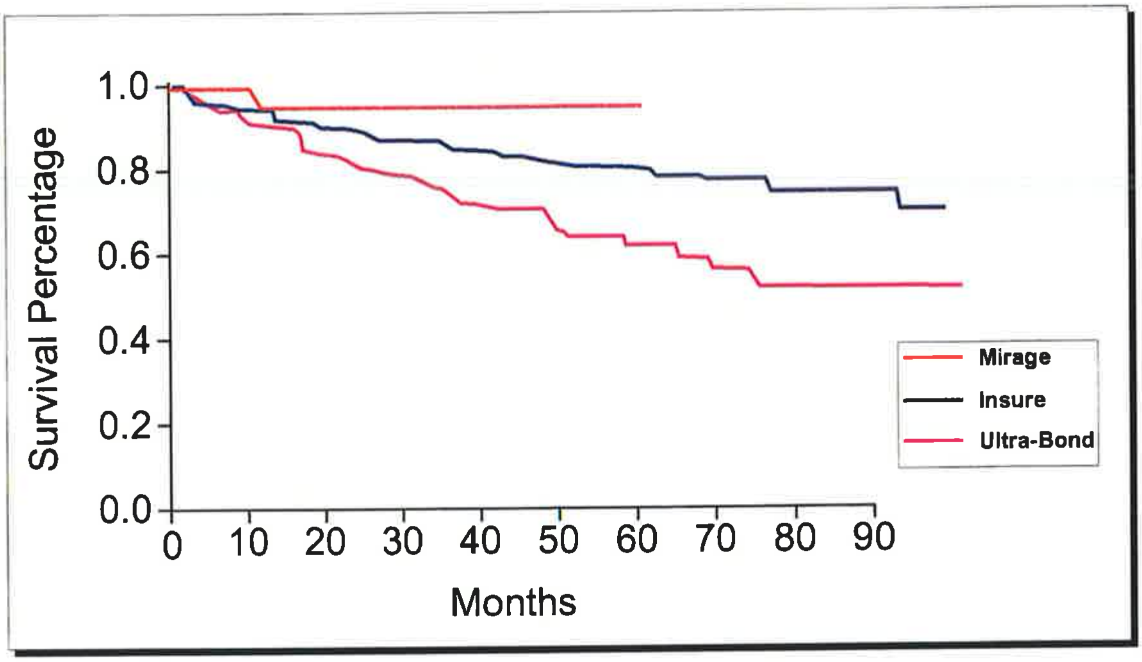


Diagram 7: Survival characteristics of restorations luted with different resin composite cements.

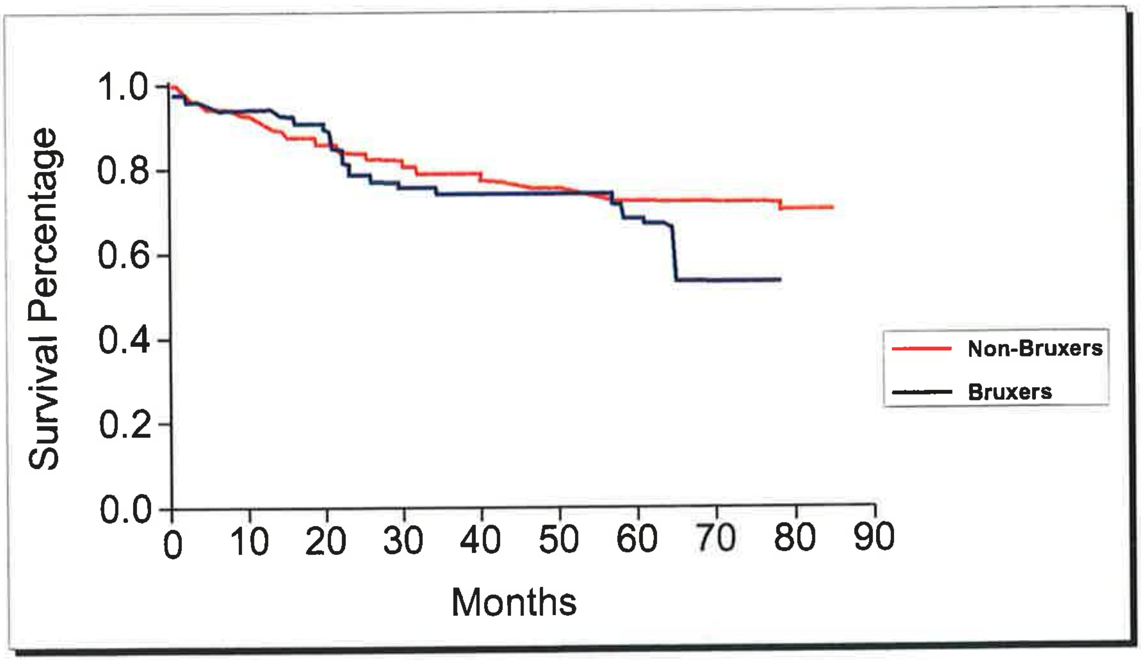


Diagram 8: Survival characteristics of restorations in patients with and without parafunctional habits.

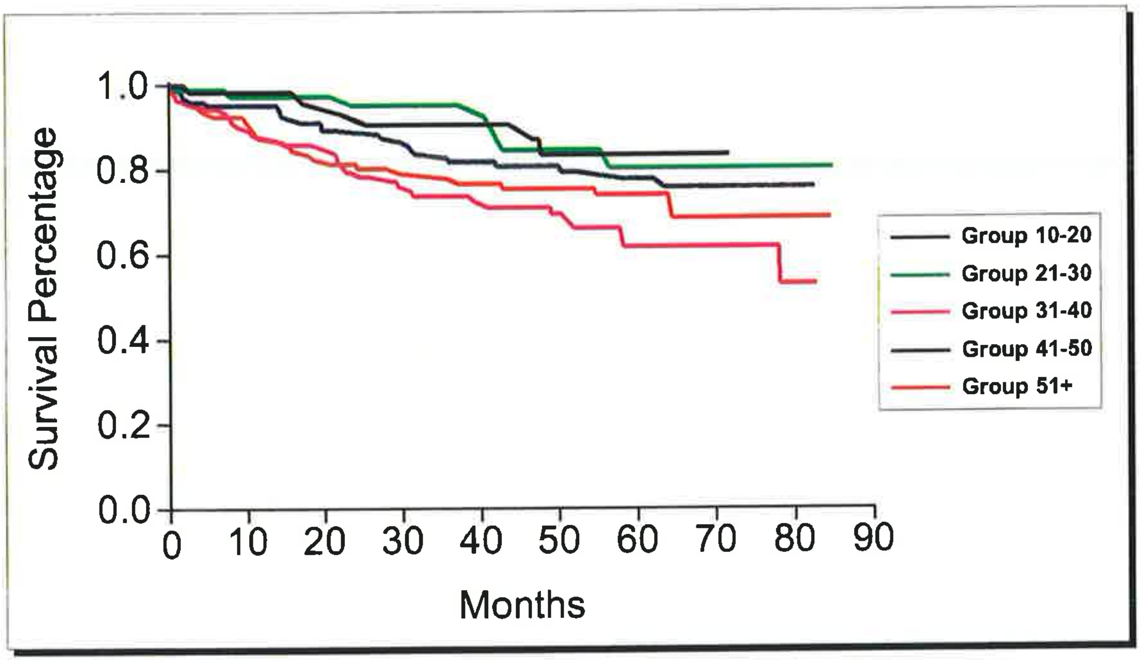


Diagram 9: Survival characteristics of different age groups.

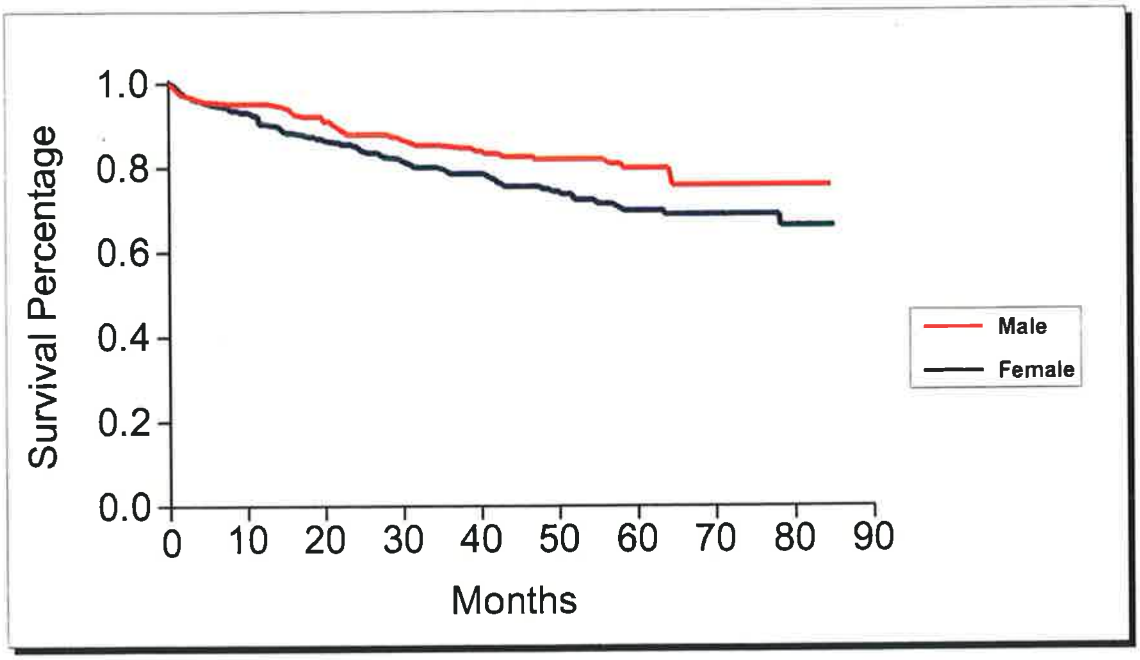


Diagram 10: Survival characteristics of restorations in male and female patients.

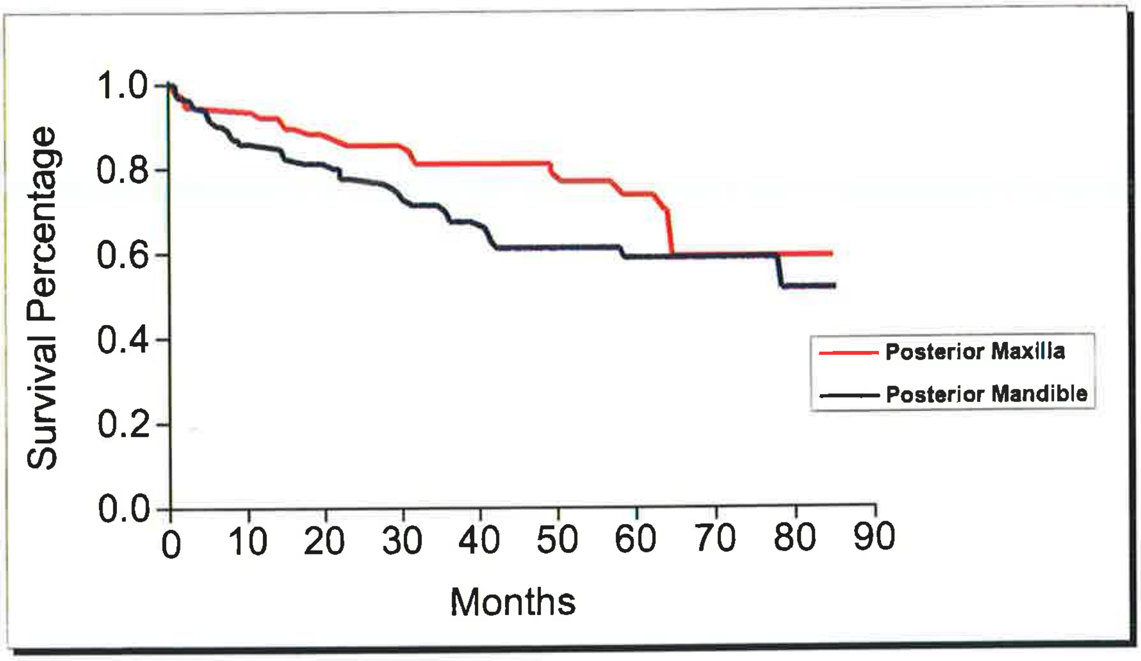


Diagram 11: Survival characteristics of onlay and shell crown restorations placed in anterior and posterior regions of maxilla and mandible.

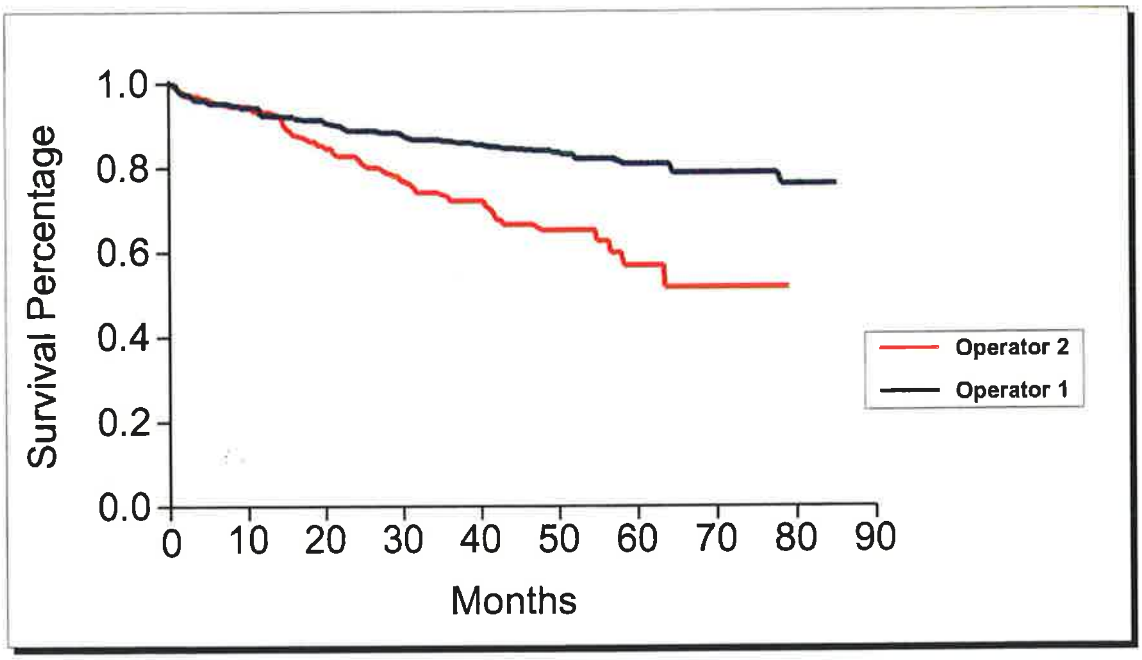


Diagram 12: Survival characteristics of restorations placed by operators 1 and 2.

5.3.3 Discussion

5.3.3.1 Introduction

In the Literature Review on the clinical behaviour of resin-bonded porcelain restorations, different types of failures occurring at variable rates were reported. The most common problems reported in the literature were restoration fracture, marginal deterioration and discolouration, post-operative sensitivity and pulpitis, and debonding (Jensen 1988, Calamia 1989, Thordrup 1991, Broome et al. 1994, Noack and Roulet 1994, Friedl et al. 1995, Isidor and Brondum 1995, Friedl et al. 1996).

5.3.3.2 Bulk Fracture

Bulk fracture comprised the highest number of failures reported in the present study (10.4% of the total number of restorations, Table 11). Some investigators reported no fractures in their studies (Krejci et al. 1992, Sorensen et al. 1995), while others reported restoration fractures either at a lower rate (Calamia 1989, Mörman and Krejci 1992, Högland et al. 1992), or at a higher rate than in the present study (Christensen and Christensen 1992, Shaini. et al. 1995, Cavel et al. 1995).

The reasons for fracture are variably presented in the literature. In the present study, the main reason for restoration fracture was thought to be excessive occlusal stress. It is obvious that other contributing factors such as restoration design, inherent defects in the porcelain, and effective bonding to tooth structure are also important. Improper bonding to tooth structure sometimes led to a combination of debonding and bulk fracture in the present study. The probable reasons for ineffective bonding in these cases were recorded as poor enamel quantity and moisture control.

Any sharp, angular uneven preparation surfaces may act as foci for stress concentrations, which may cause porcelain fracture. Glass ionomer cement bases (GIC) are often used to block out undercuts and level out uneven cavity floors. The success of resin-bonded porcelain restorations depends on uniform tooth preparation with a minimum thickness of GIC bases (Isidor and Brondum 1995). In the present study, bulk fracture for the restorations with GIC bases was approximately twice that for restorations without any bases (Table 18b). This may confirm the effect of the use of GIC bases in reducing the strength of porcelain restorations in this study. However, the operators claimed that they only used glass ionomer cement in a thin layer, as a lining on deep axial walls, and not to block out any undercuts. Any preparation unevenness or undercuts were later blocked out on the dies before fabrication of the resin-bonded porcelain restorations.

Incomplete setting, and hydration or dehydration of GIC bases at an early stage of setting reduces the mechanical strength of the material, which then impairs its bonding to tooth structure. These factors make conventional GIC bases unsuitable under resin-bonded porcelain restorations. It has also been reported that cleaning temporary cements from GIC bases is difficult, which again may compromise the bonding procedure (Milleding et al. 1995). As can be seen from Tables 19 and 20, the operators avoided using GIC bases in most of the restorations. This may have been because of their experiences with a higher numbers of failures in a few restorations based with GIC.

Any resiliency under porcelain restorations creates stress in the porcelain material, which may then lead to restoration fracture. Very thick or uneven resin composite cement lutes may produce some resiliency under porcelain restorations. In addition, a thick layer of resin composite cement will produce a larger polymerisation shrinkage, which, in turn, can create stress in the porcelain body, and/or break the bond to restoration or tooth structure. Therefore, it is essential to prepare a smooth cavity for resin-bonded porcelain restorations, and to produce an appropriate thin space for an even layer of cement. Poor-fitting restorations need thicker resin composite cement films.

Complete polymerisation of resin composite cement is another important issue in the strength of restorations, and the bond strength to tooth structure. Incomplete curing of the resin composite cement will create different regions of resiliency in the cement layer, which may also lead to porcelain fracture. Strang et al. (1987) and Linden et al. (1990) showed the significant effect of porcelain thickness and shade on the polymerisation of resin composite cements. Although light-cure composite cements polymerise well under restorations with a thickness less than 1.0 mm (Fleiter et al. 1992), the use of a dual-cure cement is recommended with thicker restorations (Milleding et al. 1995, Isidor and Brodum 1995). The latter authors, who were in favour of dual-cure cements, stated that when light-cure cements were used, the cement in the deeper areas was not completely cured, which caused flexure of the restorations. Darr and Jacobsen (1995) stated that luting agents are insufficiently cured by dual or chemical cure during the early stage of restoration placement, and the cements required 24 hours to reach their maximum cure. Therefore, the restoration may be vulnerable to loading in the first 24 hours. In the present study, Mirage adhesive cement showed the highest failures (Table 26). Ultra-Bond cement also had rather high failures. Since all the cements used by the operators were dual-cure, the difference in the failure rates may have been related to the experience of the operators at the time that Mirage and Ultra-Bond were used.

The design of resin-bonded porcelain restorations is an important factor in the strength of the restorations. Highton et al. (1987) and Watanabe et al. (1992) demonstrated a higher level of success in labial veneers with incisal coverage than in those without incisal coverage. The same results were obtained in the present study. Veneers with incisal coverage had the lowest failure rates in the study (2%, Table 11). The only failure found in these restorations was one debonding because of probable moisture contamination during cementation. A more suitable stress distribution was responsible for the better performance of the veneers with incisal coverage in the two studies mentioned previously. The only problem with this design is the larger amount of tooth reduction required, which is not as conservative as a veneer without incisal coverage. However, superior aesthetic results and resistance to fracture seem to be distinct advantages over veneers without incisal coverage. The results of the survival analysis also revealed a longer life-time for veneers with incisal coverage.

In terms of inlay/onlay designs, tooth cusp coverage by means of an onlay is recommended (Milleding et al. 1995). Although none of the inlays in the present study failed, a valid comparison with the onlays cannot be made because of there being only 9 inlays. Possibly, the operators avoided construction of porcelain inlays because of their limited usefulness in restoring occlusal form.

In the present study, a comparison of partial (onlay) and full coverage (shell crown) restorations showed that higher fracture/debonding failure rates were recorded for the onlays. An explanation for this may lie in the advantage of using full tooth coverage to produce maximum bonding between tooth and restoration. It is obvious that in the shell crown designs more peripheral enamel is available to produce a reliable bond. A more homogenous stress distribution with the shell crown designs, as compared with the onlay designs, may also contribute to the higher success of the shell crowns. Cusp flexure is more likely to occur with inlay/onlay designs than with a shell crown design. Full tooth coverage, less probability of cusp deformation, no marginal contact with opposing teeth, and more enamel available for bonding might be important factors affecting the better performance of shell crown restorations.

Onlay and shell crown restorations with metal reinforcement performed similarly overall to those without metal, as shown by the results of the survival analyses (Diagrams 3 and 4). However, failures from bulk fractures for the metal-reinforced restorations were less than half those for the non-reinforced restorations (Table 11). Therefore, the effectiveness of metal reinforcement for resin-bonded porcelain restorations, especially in high stress-bearing areas, was confirmed. Although the use of metal reinforcement for porcelain restorations sometimes needs more tooth reduction, which might also compromise the bonding to tooth structure, metal reinforces the restoration and reduces the risk of fracture. Since fracture is a common failure reason reported for resin-bonded porcelain restorations, sacrificing a small amount of tooth structure for the benefit of creating stronger restorations seems to be worthwhile. In this study, the operators used metal reinforcement for restorations of larger cavities, to avoid large bulk of porcelain. Sometimes when replacing a large amount of lost tooth structure in cases of caries or tooth fracture, or when replacing amalgam restorations, an uneven preparation is created. This will result in different porcelain thicknesses in different areas of the preparation. Sintering such a porcelain restoration creates different shrinkages, and stresses in the restoration. One way to reduce this problem is by the modification of the preparation, using GIC bases. But, to avoid potential problems associated with the use of GIC materials, an underlying metal substructure is recommended to provide an even thickness of porcelain, and to provide rigidity and resistance to deformation in the porcelain restoration (Garber and Goldstein, 1994).

The presence of voids and flaws in the porcelain is another factor which weakens the material (Øilo 1988, Kelly et al. 1989, Messer et al. 1991). Thordrup et al. (1991) compared MOD Cerec inlays with laboratory made inlays, and found some microcracks in the indirect laboratory inlays and none in the Cerec inlays.

In the present study, cantilever bridges performed much better than the fixed-fixed bridges (Table 11). This opposes the results of a study by Christensen and Christensen (1992) in which resin-bonded porcelain cantilever bridges were not recommended because of their high failure rate. Analysis of restoration survivals in the present study revealed a significantly longer lifetime for cantilever bridges than for the fixed-fixed bridges. As can be seen in Diagram 5, the survival curve for the fixed-fixed bridges dropped dramatically, whereas that of the cantilever bridges dropped more steadily. In a fixed-fixed bridge, the pontic is rigidly connected between two retainers, which have different directions of flexion when loaded. This situation leads to torquing and shear stresses in the porcelain which are beyond its flexural strength. However, when a cantilever bridge is loaded, all the unit will behave like a single tooth with less stresses in the porcelain. In addition, the higher number of units sometimes involved in fixed-fixed bridges creates complexity in its design. A fixed-fixed bridge may be more likely to flex when loaded than a cantilever bridge. Three cases of connector fractures in fixed-fixed bridges confirmed the occurrence of more deformation in these restorations.

In this study, bridges with shell crown abutment design survived better than those with veneer designs, which is in agreement with the results of Christensen and Christensen (1992). This might be because of a better load distribution along the long axis of the tooth when a shell crown abutment was chosen.

5.3.3.3 Post-Operative Sensitivity

Post-operative sensitivity is another problem commonly reported for resin-bonded porcelain restorations. Although some investigators did not report this problem in their clinical trials (Calamia 1989, Rucker 1991, Högland et al. 1992, Broome et al. 1994), most in vivo studies have reported post-operative sensitivity of various rates (Thordrup et al. 1991, Krejci et al. 1992, Sorensen 1995, Freidl et al. 1995). In the present study, at least 9% of restorations showed some post-operative sensitivity (Table 24). One possible reason for this is phosphoric acid etching of the dentine. Although the acid itself does not seem to cause irritation to the pulp, it increases dentine permeability (Pashley 1992), which may then allow access for bacteria and their products to the pulp following any microleakage.

Premature tooth contacts may also be responsible for immediate post-operative sensitivity symptoms, which will disappear after occlusal adjustment. Hypersensitivity may also occur when weak cusps are retained (Milleding et al. 1995). These cusps can be more easily bent under load or from the polymerisation shrinkage of the cement. This might be the reason for the higher post-operative sensitivity reported for onlays than for the shell crowns (Table 24). This type of sensitivity usually disappears after the high initial bonding strength of cement to tooth and porcelain surfaces decreases (Molin and Karlson, 1992). Different resin thicknesses of composite cement provide different degrees of polymerisation shrinkage and resiliency in the cement. This resiliency can produce painful symptoms in teeth (Milleding et al. 1995). The presence of microcracks in tooth structure, which can be opened by the polymerisation shrinkage of cement or by tooth function, may also create post-operative sensitivity.

GIC bases are often used to block out undercuts and to seal the dentinal tubules, to avoid post-operative sensitivity. However, in the present study, most of the instances of sensitivity occurred when GIC liners were used (Table 23). This finding opposed the results of a study by Wat and Cheung (1995) who found post-operative sensitivity associated with 64% of onlay restorations, but no symptoms in those teeth based with GIC. This emphasises the relevance of other factors such as heavy occlusal loads, tooth cracks, weak cusps, resilient load-bearing materials and preparation trauma. In the present study, the duration of sensitivity was not recorded, but it is obvious that most cases disappeared after a while, and the operators did not have to do any special treatment. However, some instances of sensitivity may persist and lead to irreversible pulpal changes (Christensen and Christensen 1992, Roulet 1995). In the present study, 2.7% of cases showed persistent pulpitis which was thought to be mainly caused by microleakage with bacterial contamination, and occlusal stresses. Of the 15 instances of persistent pulpitis, three teeth were root canal treated, and five restorations were replaced with PFM or full gold crowns. This again shows the possible influence of factors such as tooth cracks, flexible cusps, and uneven resin cement thicknesses which needed to be controlled with other alternative restorations. Seven other restorations were remade, replaced with another porcelain restoration design, or rebonded, which reveals the possible role of contamination and microleakage.

5.3.3.4 Debonding

Providing a strong bond between porcelain and tooth is critical for the success of resin-bonded porcelain restorations. However, adhesive failure has been reported frequently in the clinical evaluation of these restorations (Calamia 1989, Noak and Roulet 1994, Shaini et al. 1995). In the present study, the occurrence of debonding was very low (2.8%), and lower than reported in the studies mentioned. Polymerisation shrinkage of resin composite cement can be responsible for the breakdown of the bond to tooth, or to porcelain surfaces (Tagami et al. 1990). In resin-bonded porcelain restorations, the shrinkage stresses might be of minor importance if an even cavity floor has been prepared. However, because the construction of well-fitting restorations may be difficult with uneven cavity floor preparations, different thicknesses of cement will create different polymerisation shrinkage stresses. It has been shown that newer dentine bonding adhesives are able to overcome the initial debonding forces from polymerisation shrinkage (Swift et al. 1995).

In the present study, occlusal stresses were thought to be the most common reason for debonding, which is in agreement with a study by Lutz et al. (1991). Occlusal forces create strains in the cement layer. If an adequate bond to tooth and porcelain surfaces has been produced, then these strains can produce cohesive failure in the cement layer, which can be seen as an early debonding of the restoration (Pratt et al. 1989).

The bond strength of resin composite cement to tooth and porcelain surfaces has been shown to deteriorate over time (Bailey and Bennett 1988, Burkett et al. 1992). Microleakage and the hydrolysis of silane coupling agents may be responsible for adhesive failures over the long-term. These two factors might be additional reasons for restoration debondings in the present study.

Poor enamel quantity was reported as another possible important reason for debonding in this study. It has been shown that the bond to enamel is usually stronger than the bond to dentine (Tseng et al. 1992). Bonding strengths to deep dentine are even weaker than those to superficial dentine (Tagami et al. 1990). Where the replacement of large amounts of tooth structure is required, then bonding to dentine is unavoidable. However, the application of dentine adhesives may enhance bond strengths where there is insufficient enamel available (O'Sullivan et al. 1987, Asmussen and Munksgaard 1988, Kumatsu and Finger 1986).

In the present study, when the enamel quantity or quality was poor, and an inadequate bond to dentine was produced, the operators had to replace the failed resin-bonded porcelain restorations with other non-bonded alternatives (PFM or full gold crowns). Optimal moisture control is necessary to create reliable bonding to porcelain and tooth surfaces and, consequently, to increase the strength of the restorations (Milleding et al. 1995). In the present study, the operators did not routinely use rubber dam when cementing the restorations, and contamination of tooth or restoration surfaces could have resulted in some debonding failures. In these cases, the restorations were recemented with care, and performed well subsequently.

5.3.3.5 Parafunctional Habits

Although Table 17b demonstrated a higher failure rate in patients who bruxed (30%) than in non-bruxers (22%), the survival analysis revealed no significant difference present between the two groups. The average longevity of the restorations was almost the same in both groups (Table 17d). This shows that resin-bonded porcelain restorations can perform well in patients who brux, if the restorations are designed correctly for specific cases. For many of these patients, night guards or occlusal splints were also made, but the compliance by the patients was not known.

Since most restoration fracture failures occurred for onlays and shell crowns constructed without metal reinforcement, the results of this study suggest the use of metal substructures in restorations required for the posterior teeth. Considering the higher occurrence of bulk and chip fractures, and microfractures in the restorations of patients who brux (Table 17b), the use of metal substructures might also lead to longer survivals of restorations in this group of patients.

5.3.3.6 Age Distribution

A review of the literature by Hawthorne (1992) reported that generally, restorations of conventional types placed in very young and very old patients did not perform as well as those placed in patients from other age groups. The present study revealed quite different results, as the failure rate of restorations in younger patients (10-30 years) was very low. Survival analysis also showed significantly better success for restorations in patients aged between 10-30 years. Most of the restoration fractures, pulpitis and debondings occurred in the age groups between 31 to 51+ years.

The restorations in very young patients (10-20 years) performed very well, probably because the teeth for which the restorations had been constructed were either intact or less damaged and worn. Therefore, stronger teeth with adequate enamel were available to support and bond the restorations. However, in older patients, more tooth structure had been lost. This resulted in less enamel being available to create adequate bonding, and an increased probability of weakened cusp deformation, which consequently led to failure of the restorations. The fewer teeth present in older patients may be another reason for the higher failure rate in this group, since the magnitude of load on the remaining teeth is increased.

5.3.3.7 Arch Distribution

In this study, the failure rate of the posterior mandibular restorations was higher than the posterior maxillary restorations (Table 12). The survival analysis also revealed longer times for maxillary than for mandibular restorations. One possible reason for this is the greater difficulty with moisture control in producing an adequate bond between the restoration and tooth surfaces in the mandible, especially as rubber dam isolation was often not used. The different directions of masticatory forces in the maxilla and mandible, and the different stresses on working and non-working cusps are other possible reasons.

5.3.3.8 Operators

Although Tables 15 and 16 showed approximately the same overall percentages of failures for restorations placed by the two operators, the results of the survival analyses revealed significantly better survivals for restorations placed by operator 1. Because the restorations lined with GIC showed a higher failure rate for operator 2 (Tables 21 and 22), one possible reason for the different restoration survivals may have been less appropriate use of GIC linings by operator 2. Significantly higher failures also occurred for restorations cemented with Mirage, which was used predominantly by operator 2. However, since both operators had the same level of experience, treated similar patients, used the same porcelain material (Mirage), and one person fabricated the restorations, it is difficult to determine the reasons for the difference found in the restoration survival rates.

5.3.4 Conclusions and Recommendations

For the 536 resin-bonded porcelain restorations assessed in this clinical study, the findings for the restoration failures and survivals can be summarised as:

1) Full coverage resin-bonded porcelain restorations (shell crowns) performed better than did partial coverage restorations (onlays). Although the full-coverage restorations required more tooth reduction, their survival times were improved.

2) Onlays with metal substructures performed slightly better than those without a metal substructures. Therefore, the fabrication of restorations with metal reinforcement is recommended in selected cases, especially for posterior teeth and for restorations in patients with parafunctional habits. Although the failure rates of shell crowns with metal reinforcement were lower than those without metal reinforcement, the results of the survival analysis did not show better survival for shell crowns with metal substructures.

3) Construction of porcelain laminate veneers with incisal coverage resulted in a much lower failure rate than for laminate veneers made without incisal coverage.

4) Fixed-fixed bridges failed far more frequently and within a shorter period than did cantilever bridges. Therefore, in selected cases, construction of cantilever bridges is recommended over fixed-fixed bridges.

5) Although the restoration survivals varied for different age groups, the results of this study showed that resin-bonded porcelain restorations can be successful in any age group provided that sufficient enamel and tooth structure remain.

6) The small differences present in the failure rates and survivals of restorations placed in bruxer and non-bruxer patients, showed that resin-bonded porcelain restorations are not contraindicated in patients with parafunctional habits, provided that appropriate preparation designs and metal reinforcement are used.

7) Restorations lined with GIC showed higher failure rates than when linings were not used, although the GICs were generally used in thin layers. From the results of this study, GIC linings placed under resin-bonded porcelain restorations are not recommended. It seems that a reliable bond and reduced post-operative sensitivity can be achieved with suitable dentine bonding systems.

8) Significantly more failures occurred for restorations cemented with Mirage, than for two other resin luting cements.

9) Restorations for posterior teeth in the mandible generally showed higher failure rates than those for the maxillary teeth. Therefore, resin-bonded porcelain restorations for posterior teeth, especially for the mandible, should be appropriately designed and metal reinforcement also considered.

10) Bulk fracture was the most common failure mode recorded for the restorations in the present study. Other less frequent failure modes were debonding, pulpitis, chip fracture, colour mismatch, and connector fracture. No recurrent caries was recorded. The failure rates in this study were lower than those reported in most other studies, which demonstrates the importance of operator experience for case selection and preparation design for the success of resin-bonded porcelain restorations.

REFERENCES

ADA Council of Dental Materials, Instruments and Equipment (1994). Choosing intracoronal restorative materials. JADA 125:102-103

Anusavice K.J. (1993). Recent developments in restorative dental ceramics. JADA 124: 72-84

Anusavice K.J., Hojjatie B. (1988). Influence of incisal length of ceramic and loading orientation on stress distribution in ceramic crowns. J Dent Res 67:1371-1375

Anusavice K.J., Hojjatie B. (1992). Tensile stress in glass-ceramics: Effect of flaws and cement voids. Int J Prosthodont 5:351-358

Asmussen E., Munksgaard E.C. (1988). Bonding of restorative resins to dentine: status of dentine adhesives and impact on cavity design and filling technique. Int J Dent; 38: 97-104

Bailey L.F., Bennett R.J. (1988). Dicor surface treatments for enhanced bonding. J Dent Res 67: 925-931

Banks R.G. (1990). Conservative posterior ceramic restorations: A literative review. J Prosthet Dent 63: 619-626

Barghi N., Berry T.G. (1994). Effect of heat treatment of silanated porcelain on bonding. J Dent Res (IADR), 73: 319, No: 1738

Blackman R., Barghi N., Duke E. (1990). Influence of ceramic thickness on the polymerisation of light-cured resin cement. J Prosthet Dent 63: 295-300

Broderson S.P. (1994). Complete-crown and partial-coverage tooth preparation designs for bonded cast ceramic restorations. Quintessence Int 25: 535-539

Broome J.C., Troiani L.K., Leinfelder K.F. (1994). Two-year clinical evaluation of ceramic inlays. J Dent Res (IADR), 73: 191, No: 713

Burke F.J.T., Qualtrough A.J.E. (1994). Aesthetic inlays: composite or ceramic? Br Dent J 22: 53-59

Burkett L., Burgess J.O., Robbins J.W. (1992). Shear bond strength of six porcelain repair methods. J Dent Res (AADR), 71: 1, No: 445

Calamia J.R., Vaidyanathan J., Vaidyanathan T.K., et al. (1987). Shear bond strength of etched porcelains. J Dent Res (IADR), 66: 296, No: 1096

Calamia J.R. (1989). Clinical evaluation of etched porcelain veneers. Am J Dent 2: 9-15

Cambell S.D. (1989). A comparative strength study of metal ceramic and all-ceramic esthetic materials: Modulus of rupture. J Prosthet Dent 62: 476-479

Castellani D., Baccetti T., Giovannoni A., Bernardini U.D. (1994). Resistance to fracture of metal ceramic and all-ceramic crowns. Int J Prosthodont 7: 149-154

Cavel W.T., Blankanau R.J., Latta M.A.et al. (1995). Bonded Dicor Crowns: 4 year report. J Dent Res (AADR), 74: 166, No: 1239

Chan D.C.N., Jensen M.E., Sheth J., Sigler T. (1987). Shear-bond strengths of etched porcelain bonded with resin to enamel. J Dent Res (IADR, AADR), 66: 245, No: 1109

Chang T.C., Nguyen T.D., Duong J.H., Ladd G.D. (1994). Tensile strength of dual-cure cements between ceramics and enamel. J Dent Res (IADR), 73: 229, No: 1018

Christensen G.J. (1995). A void in U.S. restorative dentistry. JADA 126: 244-247

Christensen R., Christensen G. (1992). Service potential of all-ceramic fixed prostheses in areas of varying risk. J Dent Res (AADR), 71: 320, No: 1716

Cochran M.A., Carlson T.J., Moore B.K. et al. (1988). Tensile bond strength of five porcelain repair systems. Oper Dent 13: 162-167

Clinical Research Associates (1994). Alteratives for Class 2 restorations. CRA Newsletter 18: 1-2

Darr A.H., Jacobsen P.H. (1995). Conversion of dual-cure luting cements. J Oral Rehab 22: 43-47

Diaz-Arnold A.M. Aquilino S.A. (1989). An evaluation of the bond strength of four organosilane materials in response to thermal stress. J Prosthet Dent 62: 257-260

Diaz-Arnold A.M., Schneider R.L., Aquilino S.A. (1989). Bond strength of intraoral porcelain repair materials. J Prosthet Dent 61: 305-309

Dickinson A.J.G., Moore B.K. Harris R.K. et al. (1989). A comparison study of the strength of aluminous porcelain and all-ceramic crowns. J Prosthet Dent 61: 297-304

Dietschi D., Maeder M., Meyer J.M. et al. (1990). In vitro resistance to fracture of porcelain inlays bonded to tooth. Quintessence Int. 21: 823-831

Dixon W.J. (1992). BDP Statistical Software Vol 2. Berkeley: University of California Press (BMDP software program IL)

Doyle M.G., Goodcare C.J., Munoz C.A. et al. (1990). The effect of preparation design on the breaking strength of Dicor crowns: Part 3. Int J Prosthodont 3: 327-340

Ellison J.A., Lugassy A.A., Setcos J.C. et al. (1992a). Clinical trial of molar cast glass ceramic crowns, 4-year findings. J Dent Res (AADR), 71: 207, No: 815

Ellison J.A., Lugassy A.A., Setcos J.C. et al. (1992b). Clinical trial of cast glass ceramic crowns, 7-year findings. J Dent Res (AADR), 71:207, No: 816

Etemadi S. (1994). In vitro aspects of etched-porcelain resin-bonded restorations. Essay- The University of Adelaide

Ferrari M. (1991). Cement thickness and microleakage under Dicor crowns: An in vivo investigation. Int J Prosthodont 4: 126-131

Fleiter B., Le Denmat D., Estrade D., Degrange M. (1992). Polymerisation of the adhesive cement according to the nature of the ceramic. J Dent Res (IADR abstract); 71: 566; No:406

Friedl K.H., Schmalz G., Hiller K.A., Saller A. (1995). In vivo evaluation of a feldspathic ceramic system: Two year results. J Dent Res (IADR), 74: 405, No: 35

Friedl K.H., Schmalz G., Hiller K.A., Saller A. (1996). In vivo evaluation of a feldspathic ceramic system: 2-year results. J Dent. 24: 25-31

Friedlander L.D., Munoz C.A., Goodcare C.J. et al. (1990). The effect of tooth preparation design on the breaking strength of Dicor crowns: Part 1. Int J Prosthodont 3: 159-168

Fuzzi M., Bonfiglioli K., Difebo G, Marin C., et al. (1989). Posterior porcelain inlay: clinical procedures and laboratory techniques. In J Periodont Rest Dent 9: 275-277

Garber D.A. Goldstein R.E., (1994a) Porcelain and Composite Inlays and Onlays. Esthetic Posterior Restorations. Quintessence Publishing Co., Chicago, Pages 104-113

Garber D.A., Goldstein R.E. (1994b). Porcelain and Composite Inlays and Onlays. Esthetic Porterior Restorations. Quintessence Publishing Co., Chicago, Pages 38-47

Glossary of Prosthodontic Terms, 6th ed. (1994). The Academy of Prothodontics. J Prosthet Dent 71: 41-112

Hawthorne W.S. (1992). Factors invovled in the deterioration and failure of dental restorations. Essay, The University of Adelaide

Highton R., Caputo A.A., Matyas J. (1987). A photoelastic study of stresses on porcelain laminate preparations. J Prosthet Dent 58: 157-161

Hofmann N., Haller B. (1991). Shear strength of composite luted to ceramics. A comparison of three ceramic materials. International Symposium on Computer Restorations, Zurich Dental Institute, University of Zurich 1991, Pages 151-161

Hoglund C., Van Dijken J., Olofsson A.L. (1992). A clinical evaluation of adhesively luted ceramic inlays. Swed Dent J 16: 169-171

Hondrum S.O., O'Brien W.J. (1988). The strength of alumina and magnesia core crowns. Int J Prosthodont 1: 67-72

Hosokawa E., Barreriro M.M., Macchi R.L. (1995). Adhesion of composite resin to porcelain surfaces. J Dent Res (IADR, Argentine Division), 74: 731, No: 15

Hui K.K.K. Williams B., Holt R.D. (1991). A comparative assessment of the strengths of porcelain veneers for incisor teeth dependent on their design characteristics. Br Dent J 171: 51-55

Isenberg B.P., Essing M.E., Leinfelder K.F., Mueninghoff L.A. (1991). Clinical evaluation of marginal integrity: Two years results. International Symposium on Computer Restorations, Zurich Dental Institute, University of Zurich, Pages 163-172

Isidor F., Brondum K. (1995). A clinical evaluation of porcelain inlays. J Prosthet Dent 74: 140-144

Jedynakiewicz N., Martin N. (1993). CAD-CAM in Restorative Dentistry: The Cerec Method, 3rd ed. Liverpool University Press, Liverpool

Jensen M.E. (1988). A two-year clinical study of posterior etched-porcelain resin-bonded restorations. Am J Dent 1: 27-33

Jablonski S. (1992). Jablonski's Dictionary of Dentistry. Malabor : Krieger Publishing Co.

Jong G., Zive M., Kugel G. et al. (1992). Surface treatment effects on porcelain-composite bonding. J Dent Res (AADR), 71: 277, No: 1372

Kawai K., Isenberg B.P., Leinfelder F.L. (1994). Effect of gap dimension on composite resin cement wear. Quintessence Int. 25: 53-58

Kelly J.R., Campbell S.D., Bowen H. (1989). Fracture-surface analysis of dental ceramics. J Prosthet Dent 62: 536-541

Kelly J.R. (1994). Extrapolation from strength: Caveat Emptor. Transactions, Academy of Dental Materials, Proceding of Conference on Lifetime Prediction and Failure Analysis of Restorative Materials. 7: 16-22

Kelly J.R., Tesk J.A., Sorensen J.A. (1994). Clinical failure of In-Ceram FPDs: Fractography, stress and probability of failure analysis. J Dent Res (IADR), 73: 191, No: 718

Kelly P.G. (1995). Direct-Milled Dental Restorations: A Review of the Literature. Essay for the MDS programme. The University of Adelaide

Kern M., Fechtig T., Strub J.R. (1994). Influence of water storage and thermal cycling on the fracture strength of all-porcelain, resin-bonded fixed partial dentures. J Prosthet Dent, 71: 251-256

Klaiber B., Haller B., Heinemann C., Hofmann N. (1994). Effect of dentine adhesives on marginal adaptation of bonded tooth coloured inlays. J Dent Res (IADR), 73: 136, No: 277

Komatso M., Finger W. (1986). Dentine bonding agents: correlation of early bond strength with margin gaps. Dent Mater 2: 257-262

Krejci I., Krejci D., Lutz F. (1992). Clinical evaluation of a new pressed glass ceramic inlay material over 1.5 years. Quintessence Int. 23: 181-186

Krejci I., Lutz F., Reimer M (1993). Marginal adaptation and fit of adhesive ceramic inlays. J Dent 21: 39-46

Lacy A.M. Laluz J., Watanabe L.G. , et al. (1988). Effect of porcelain surface treatment on the bond to composite. J Prosthet Dent 60: 288-291

Lacy A.M., Wada C., Du W., Watanabe L. (1992). In vitro microleakage at the gingival margin of porcelain and resin veneers. J Prosthet Dent 67: 7-10

Leinfelder K.F. (1994). After amalgam what? Other materials fall short. JADA 125: 586-589

Linden J.J., Swift E.J., Davis B.K. (1990). Effect of porcelain opacity on curing of composite resin cements. J Dent Res (IADR), 69: 209, No: 806

Lutz F., Krejci I., Barkakow F. (1991). Quality and durability of marginal adaptation in bonded composite restorations. Dent Mater 7: 107-113

Malament K.A., Grossman D.G. (1992). Bonded vs non-bonded Dicor crowns: Four-year report. J Dent Res (AADR), 71: 321, No: 1720

McInnes-Ledoux P.M., Ledoux W.R., Weinberg R. (1989). A bond strength study of luted castable ceramic restorations. J Dent Res 68: 823-825

McLean J.W. (1974). The Science and Art of Dental Ceramics, vol. 1. Quintessence Publishing Co., Chicago,. Page 14

McLean J.W. Kedge M.I. (1987). High-strength ceramics. Quintessence Int. 18: 97-106

Messer P.F. Piddcok V., Lloyd C.H. (1991). The strength of dental ceramics. J Dent 19: 51-55

Milleding P., Örtengren M., Kalsson S. (1995). Ceramic inlay systems, some clinical aspects. J Oral Rehabil 22: 571-580

Molin M. And Karlsson S. (1992). A clinical evaluation of the Optec inlay system. Acta Odontol Scand 50: 227-233

Mörmann W., Brandestini M. (1989). Die CEREC computer reconstruction. Inlays, Onlays and Veneers. Quintessenz, Berlin

Mörmann W., Gotsch T., Krejci I. et al. (1991). Clinical status of 94 Cerec ceramic inlays after 3 years in situ. International Symposium on Computer Restorations, Zurich Dental Institute, University of Zurich Dental Institute, University of Zurich, Pages 355-364

Mörmann W., Krejci I. (1991). Clinical and SEM evaluation of Cerec inlays after 5 years in situ. International Symposium on Computer Restorations, Zurich Dental Institute, University of Zurich, Pages 25-32

Mörmann W., Krejci I. (1992). Computer-designed inlays after 5 years in situ: clinical performance and scanning electron microscopic evaluation. Quintessence Int 23: 109-115

Munoz C.A., Goodcare C.J., Friedlander L.D. et al. (1990). The effect of preparation design on the breaking strength of Dicor crowns: Part 2. Int J Prosthodont 3(3): 241-248

Nathanson D., Vongphantuset R., L'Herault R. (1992). Bond strengths of luting resins to etched glass ceramic in vitro. J Dent Res (AADR), 71: 254, No: 1186

Noack M.J. and Roulet J.F. (1994). Survival rates and modes of failure of Dicor inlays after four years. J Dent Res (IADR), 73: p: 196, No: 759

O'Neal S.J., Miracle R.L., Leinfelder K.F. (1993). Evaluating interfacial gaps for esthetic inlays. J A D A 124: 48-54

Øilo G. (1988). Flexural strength and internal defects of some dental porcelains. Acta Odontol Scand 46: 313-322

Øilo G., Olsson S. (1990). Tensile bond strength of dentine adhesives: a comparison of materials and methods. Dent Mater 6: 138-144

Olin P.S., Holtan J.R., Jankowski J. (1992). Effect of fatigue on the microleakage of porcelain veneers. J Dent Res (AADR), 71: 1, No: 444

O'Sullivan B.P., Johnson P.F. (1987). Bond strength of luting composite to dentine with different bonding systems. J Prosthet Dent 58: 171-175

Pashley D.H. (1992). Effect of acid etching on the pulpodentine complex. Oper Dent 17:229-242

Peters M.C.R.B., De Vree J.H.P., Brekelmans W.A.M. (1993). Distribution crack analysis of ceramic inlays. J Dent Res 72: 1537-1542

Plueddemann E.P. (1991). Silane Coupling Agents. Plenum Press, New York.

Pospiech P., Pammelsberg P., Goldhofer G., Gernet W. (1994). Stress distribution in all-porcelain resin-bonded bridges, A 3-D finite element analysis. J Dent Res (IADR), 73: 197, No: 761

Pratt R.C., Burgess J.O., Schwartz R.S. et al. (1989). Evaluation of bond strength of six porcelain repair systems. J Prosthet Dent 62: 11-13

Qualtrough A.J.E., Cramer A., Wilson N.H.F. et al. (1991). An in vitro evaluation of marginal integrity of a porcelain inlay system. Int J Prosthodont 4: 517-523

Qualtrough A.J.E., Wilson N.H.F. (1996). A 3-year clinical evaluation of a porcelain inlay system. J Dent 24: 317-323

Reid J.S. Saunders W.P. Baidas K.M. (1993). Marginal fit and microleakage of indirect inlay systems. Am J Dent 6: 81-84

Reinelt C., Pelka M., Kramer N., Petschelt A. (1995). Inlays and onlays with IPS Empress. J Dent Res (IADR, European Division), 74: 938, No: 220

Rosenstiel S.F., Porter S.S. (1987). Apparent fracture toughness of dental porcelain with a metal substructure. Dent Mater 4: 187-190

Rosenstiel S.F., Porter S.S. (1989). Apparent fracture toughness of all-ceramic crown systems. J Prosthet Dent 62: 529-532

Roulet J-F., (1995). The longevity of glass ceramic inlays. J Dent Res (IADR), 74: 405, No: 36

Roulet J-F., Herder S. (1991a). Bonded Ceramic Inlays. Quintessence Publishing Co., Chicago, Pages 16-31

Roulet J-F., Herder S. (1991b). Bonded Ceramic Inlays. Quintessence Publishing Co., Chicago, Pages 34-36

Roulet J-F., Soderholm K.J.M. (1992). Influence of water storage on ceramic-composite bond strength. J Dent Res (AADR), 71: 254, No: 1185

Rucker L.M., richter W., MacEntee M., Richardson A. (1990). Porcelain and resin veneers clinically evaluated: 2 -year results. JADA 121; 5: 594-596

Scherrer S.S., De Rijk W.G., Belser U.C. (1994). Fracture resistance of three all-ceramic crown systems compared to extracted teeth. J Dent Res (IADR), 73: 190, No: 711

Scherrer S.S., Rijk W.G., Pisa V., Belser U.C. (1995). Lifetime determination of all-ceramic restorations. J Dent Res (AADR), 74: 159, No: 1178

Seghi R.R., Daher T., Caputo A. (1990). Relative flexural strength of dental restorative ceramics. Dent Mater 6: 181-184

Shaini F.J., Marquis P.M., Shortall A.C.C. (1995). Clinical performance of porcelain laminate veneers fitted in Birmingham Dental Hospital. J Dent Res (IADR, British Division), 74: 895, No: 583

Shortall A.C., Fayyad M.A., Williams J.D. (1989). Marginal seal of injection-moulded ceramic crowns cemented with three adhesive systems. J Prosthet Dent 61: 24-27

Simonsen R.J., Calamia J.R. (1983). Tensile bond strength of etched porcelain. J Dent Res (AADR), 62: 297, No: 1154

Snuggs H.M., Powell C.S., Cox C.F. et al. (1992). Clinical evaluation of cervical lesions after acid etching and restoration. J Dent Res (AADR), 71: 188, No: 659

Sorensen J.A., Kang S.K., Avera S.P. (1991a). Porcelain-composite interface microleakage with various porcelain surface treatment. Dent Mater 7: 118-123

Sorensen J.A., Engleman M.J., Torres T.J. et al. (1991b). Shear bond strength of composite resin to porcelain. Int J Prosthodont 41: 17-23

Sorensen J.A, Strutz J.M. Avera S.P. et al. (1992). Marginal fidelity and microleakage of porcelain veneers made by two techniques. J Prosthet Dent 67: 16-22

Sorensen J.A., Fanuscu M.I. Choi G., Mito W. (1995). Status of clinical trail on Empress Crowns. J Dent Res (AADR), 74: 159, No: 1182

Stacy G.D. (1993). A shear stress analysis of the bonding porcelain veneers to enamel. J Prosthet Dent 70: 395-402

Stangel I., Nathanson D., Hsu C.S. (1987). Shear strength of the composite bond to etched porcelain. J Dent Res 66: 1460-1465

Stanley H.R., Bowen R.L., Cobb E.N. (1988). Pulp response to a dentine and enamel adhesive bonding procedure. Oper Dent 13: 107-113

Stassinakis A., Zehnder M., Hugo B., Hotz P. (1996). Cavity preparation of adhesive onlays. A cross sectional comparison study between university staff members and private practitioners. J Dent Res 75: 166, No: 1185

Stokes A.N., Hood J.A.A., Tidmarsh, B.G. (1988). Effect of 6-month water storage on silane-treated resin/porcelain bonds. J Dent 16: 294-296

Strang R., McCrosson J., Muirhead G.M., Richardson S.A. (1987). The setting of visible light-cured resins beneath etched porcelain veneers. Br Dent J 163: 149-151

Swift E.J., Perdigao J., Heymann H.O. (1995). Bonding to enamel and dentine: A brief history and state of the art. Quintessence Int 26: 95-110

Tagami J., Tao L., Pashley D.H. (1990). Correlation among dentine depth, ermeability, and bond strength of adhesive resins. Dent Mater 6: 45-50

The Dental Advisor (1992). Alteratives to amalgam. 9: 1-7

Thordrup M., Isodor F., Hörsted-Bindslev P. (1991). Cerec or laboratory inlay? International Symposium on Computer Restorations, Zurich Dental Institute, University of Zurich, Pages 91-102

Tjan A.H.L., Nemetz H. (1988). A comparison of the shear bond strength between two composite resins and two etched ceramic materials. Int J Prosthodont 1: 73-79

Tjan H.L.A., Dunn J.R., Sanderson I.R. (1989). Microleakage pattern of porcelain and castable ceramic laminate veneers. J Prosthet Dent 61: 276-282

Tseng E.Y., Cooly R.L., Evans J.G. (1992). Porcelain to dentine bond strength with NTG-GMA/BPDM adhesive. J Dent Res (AADR), 71: 133, No: 220

Tyas M.J. (1994). Dental amalgam-what are the alternatives? Int Dent J 44: 303-308

Ubassy G. (1992) Shape and Color. The Key to Sucessful Ceramic Restorations. Quintessence Publishing Co., Chicago, Pages 119-121

Van Meerbeek B., Inokohshi S., Willems G. et al. (1992). Marginal adaptation of four tooth-coloured inlay systems in vivo. J Dent 20: 18-26

Wat P., Cheung G.S.P. (1995). Incidence of post-operative sensitivity following porcelain onlay restorations: preliminary results. Asian J Aesthet Dent, 3: 3-7

Watanable F., Lorey H., Fukuda H., Hata Y. (1992). Stress analysis of ceramic laminate veneers at loading using FEM. J Dent Res (IADR Abstract), 71: 661, No: 1163

Weaver J.D., Johnson G.H., Bales D.J. (1991). Marginal adaptation of castable ceramic crowns. J Prosthet Dent 66: 747-753

White K.C., Snuggs H.M. Ramus O.L. (1992a) Histologic evalution of a new bonding agent. J Dent Res (AADR), 71: 279, No. 1386

White K.C., Cox C.F., Kanca J. et al. (1992b). Histologic pulpal response of acid etching vital dentine. J Dent Res (AADR), 71: 188, No: 658

Wolf D.M., Powers J.M., O'Keefe K.L. (1992). Bond strength of etched or sandblasted porcelain. J Dent Res (AADR), 71: 277, No: 1371

Yen TW., Blackman R.B., Baez R.J. (1993). Effect of acid etching on the flexural strength of a feldspathic porcelain and a castable glass ceramic. J Prosthet Dent 70: 224-233

Zaimoglu A., Karaagaclioglu L., Uctasli. (1992). Influence of porcelain material and composite luting resin on microleakage of porcelain laminate veneers. J Oral Rehabilitation 19: 319-327

Zwemer T.J. (1993). Boucher's Clinical Dental Terminology. A glossary of Accepted Terms in all Disciplines of Dentistry. Mosby, St. Louis

Appendix I

MATERIALS DETAILS

1- **Mirage Porcelain**: Chameleon Dental Products, Kansas City, KS, USA.

2- **Mirage Die-Locator Tray**: Chameleon Dental Products, Kansas City, KS, USA.

3- **Dial Calliper**: Rabone Chesterman Ltd, Switzerland.

4- **Lab Putty**: Condensation type. Coltène/Whaledent Inc., Mahwah, NJ, USA.

5- **Camera**: Minolta SRT-202 body with Vivitar 95 mm f2.8 macrolens, 2 x teleconventer, and Dine ring flash.

6- **Film**: Ektachrome 100 Plus colour transparency film.

7- **Resin Composite Cements** (Light cured/Dual cured):
   - a: Mirage: Chameleon Dental Products, Kansas City, KS, USA.
   - b: Insure: Cosmedent, Chicago, IL, USA.
   - c: Ultra-Bond: Den-Mat Corp., Santa Maria, CA, USA.
   - d: Porcelite: Kerr Corp., Orange, CA, USA.
   - e: Sono-Cem: ESPE GmbH, Seefeld, Germany.
   - f: Dicor: Dentsply Int., York, PA, USA.

Appendix II

PROFORMAS

Dr S. Etemadi
Department of Dentistry
University of Adelaide

EPRB Restorations - Class II Onlay Preparation Design (dies)

[Box No.:
Date:]

File: 5 1 | Form: 1 | 4 Reg. No.: 5 1 | 9 Surname, Initial | 25 DOB: Day Mnth Yr

32 Times Restored | Rest. No. | Tooth FDI | Surfaces O M D B L

Veneer = 1
Shell cr. = 2
Inlay = 3
Onlay = 4
Veneer + Incisal = 9

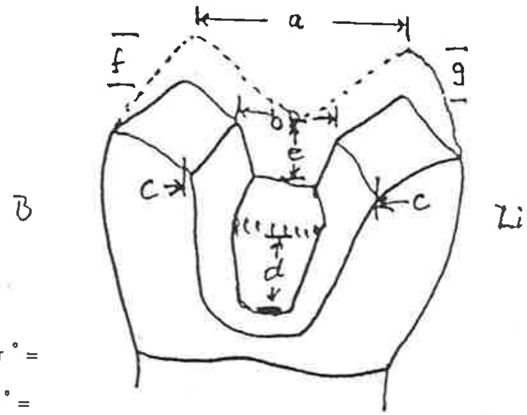
[Date placed:
Date replaced:]

Measurements [0.00mm] (Use silicone for working side contacts only)

		a.	b.	c.	d.	e.	f.	g.	
45	MO	Intercuspal width	Isthmus width	Proximal width	Height axial wall	Depth occlusal floor from central fissure	B.Cusp reduction	Li. Cusp reduction	
62	DO								

General features [0 = no, 1 = yes]

	MO			DO
79		gingival margins in dentine/cementum	87	
		fissures left at cavosurface margins		
		margins bevelled occlusally and gingivally		
		opposing tooth contacts on margins		
		angular cavosurface margin outlines		
		sharp internal line/point angles		
		retention grooves absent		
86		preparation taper < 20°	94	
			95	



Mesial taper ° =

Distal taper ° =

Duplicate examination = D

100 proximal box(es) | 101 occlusal box | 102 Metal reinforcement

EPRB Restorations

Dr S. Etemadi
Department of Dentistry
University of Adelaide

File [5][1] Form [2] 4 [5][1][ ][ ][ ] Reg. No.
9 [ ] Surname, Initial
25 DOB [ ][ ] Day [ ][ ] Mth [ ][ ] Yr
[ ] M=1 F=2
32 [ ] (with pontic fo bridges)

33 General
- Brux, Attrition
- Heavy Stain
- High Caries
- Erosion, Abrasion
- Al. bone Loss

38 F.D.I. Restn/ Pontic

Restoration: 1. Veneer 2. Shell 3. Inlay 4. Onlay 5. FF Br 6. FM Br 7. C Br 8. Chip 9. Veneer & Incisal edge
- No. of abuts
- No. of pontics
- Metal rests
- 44 Metal reinf.

Base: 1. None 2. GIC 3. Ca(OH) 4. Other
Porc.: 1. Mirage 2. Duceram 3. Dicor
Cement: 1. Mirage 2. Insure 3. Ultrabond 4. Porcelite 5. Sono-Cem 6. Dicor 7. Other e.g. Hg scare
Oper.: 1. PD 2. JG 3. JI 4.
1.=EPI

50 Tooth
- RCF
- Discol.
- Poor enamel
- Post-op sensitive (shortterm)

54 Occlusal Contacts
- Work.
- Balan.

56 Denture
- Abuts
- Opposes

59 Reasons for Placement
1.By patient 2.By operator
Tooth: 1.loss 2.fract. 3.discol. 4.wear 5.RCF 6.malocl. 7.defect 8.sensitive 9.abutment
Restn.: 1.fract. 2.caries 3.microleakage 4.discolored/shape poor 5.contacts - food impactions 6.loss 7.Malocl. 8.wear
62 Other e.g. Hg scare

Inserted [ ][ ] Day [ ][ ] Mth [ ][ ] Yr

69 Restn. No. [ ][ ][ ][ ][ ] Times restored
[ ]
Obs./Fail Date [ ][ ] Day [ ][ ] Mth [ ][ ] Yr

81 Failure Type — True
- Sensitive Pulpitis
- 2° caries
- Food impact.
- Colour mismatch
- Debond

86 Porcelain
- Bulk fract.
- Chip fract.
- Connect fract. br.
- Other e.g. microfract

- Apparei

92 Failure reason
- Micro-leakage
- Poor anat./ prepn.
- Poor etch contamin.
- Poor enamel quality
- Poor enamel quantity
- 97 Occlus. stress
- Tooth mobile
- Not sealed
- Poor colour match
- Other e.g. trauma

102 Treatment
- None, adjust
- Porc. repair by resin
- Remake
- Replace differ. material
- Rebond
- RCF
- Other

109 Deterioration
- Gingivitis
- Surf. rough
- Surf. stain
- Marg. stain
- Marg. fract.
- Colour mismatch
- Porc. cracks

116 Wear
- Porc. restn.
- Opposing teeth, restns
- Resin cement
- Antagonist absent

125 [ ]

131 Duplicate exam [ ]

Appendix III

RESULTS OF PREPARATION DIMENSIONS (Section 5.1)

Table 1: Distribution of restorations types in maxilla and mandible (N = 105)

Restoration Type	Maxilla		Mandible		Total	
	Number	Percentage	Number	Percentage	Number	Percentage
Shell Crown	21	20	25	24	46	44
Onlay	31	29	26	25	57	54
Inlay	1	1	1	1	2	2
Total	53	50	52	50	105	100

Table 2: Number of failed restorations in maxilla and mandible (N=25)

Restoration Type	Maxilla		Mandible		Total
	Molar	Premolar	Molar	Premolar	
Shell Crown	1	1	5	4	11
Onlay	6	2	5	1	14
Inlay	0	0	0	0	0
Total	7	3	10	5	25

Table 3: Failure type for each restoration. (N=25)

Restoration Type	Fracture		Debonding		Pulpitis		Chip		Total
	Molar	Premolar	Molar	Premolar	Molar	Premolar	Molar	Premolar	
Shell Crown	4	1	0	1	2	3	0	0	11
Onlay	7	0	0	1	3	1	1	1	14
Total	11	1	0	2	5	4	1	1	25

Table 4: Percentages of different surfaces involved in preparations for each type of restoration (N=105)

Preparation Surfaces	Shell Crown %	Onlay %	Inlay %
1 Surface (Occlusal)	0	0	0.95
2 Surfaces (MO, DO)	0	6.7	0.95
2 Surfaces (BO, OL)	0	0	0
3 Surfaces (MOD)	0	40	0
4 Surfaces (All Surfaces)	43.8	7.6	0
Total	43.8	54.3	1.9

Table 5a: Number and dimension of intercuspal width measurements in mesial and distal of surviving premolars and molars for Shell Crowns (N=45)

Tooth	Cavity Site	3-3.9 mm	4-4.9 mm	5-5.9 mm	≥6 mm	Total	Mean	SD	Max.	Min.
Premolar	Mesial	2	12	6	2	22	4.6	0.8	6.3	3.0
	Distal	0	2	0	1	3	5.0	1.1	6.3	4.4
Molar	Mesial	1	2	3	5	11	5.7	0.9	7.0	3.9
	Distal	0	1	3	5	9	6.8	0.8	7.0	4.3
Total		3	17	12	13	45	-	-	-	-

Table 5b: Number and dimension of intercuspal width measurements in mesial and distal of failed premolars and molars for Shell Crowns (N=11)

Tooth	Cavity Site	3-3.9 mm	4-4.9 mm	5-5.9 mm	≥6 mm	Total	Mean	SD	Max.	Min.
Premolar	Mesial	-	-	-	-	-	-	-	-	-
	Distal	-	-	-	-	-	-	-	-	-
Molar	Mesial	0	1	2	3	6	5.7	0.8	6.7	4.4
	Distal	0	0	0	5	5	6.8	0.6	7.5	6.0
Total		0	1	2	8	11	-	-	-	-

Table 6a: Number and dimension of intercuspal width measurements in mesial and distal of premolars and molars for surviving Onlays (N=59)

Tooth	Cavity Site	3-3.9 mm	4-4.9 mm	5-5.9 mm	≥6 mm	Total	Mean mm	SD	Max. mm	Min. mm
Premolar	Mesial	4	4	1	2	11	4.5	0.9	6.2	3.5
	Distal	0	1	1	4	6	6.1	0.8	7.1	4.9
Molar	Mesial	0	3	8	12	23	5.8	0.8	6.9	4.0
	Distal	0	3	7	9	19	5.8	0.8	7.5	4.1
Total		4	11	17	27	59	-	-	-	-

Table 6b: Number and dimension of intercuspal width measurements in mesial and distal of premolars and molars for failed Onlays (N=21)

Tooth	Cavity Site	3-3.9 mm	4-4.9 mm	5-5.9 mm	≥6 mm	Total	Mean mm	SD	Max. mm	Min. mm
Premolar	Mesial	-	-	-	-	-	-	-	-	-
	Distal	-	-	-	-	-	-	-	-	-
Molar	Mesial	1	1	3	6	11	5.8	0.9	7.0	3.4
	Distal	0	0	3	7	10	6.4	0.7	7.5	5.5
Total		1	1	6	13	21	-	-	-	-

Table 7a: Number and dimension of isthmus width measurements in mesial and distal of <u>surviving</u> premolars and molars for Shell Crowns (N=21)

Tooth	Cavity Site	<1 mm	1-1.9 mm	2-2.9 mm	3-3.9 mm	≥4 mm	Total	Mean	SD	Max.	Min.
Premolar	Mesial	0	0	2	2	3	7	3.6	0.9	4.8	2.2
	Distal	0	0	1	0	2	3	3.9	1.0	4.8	2.9
Molar	Mesial	0	0	2	2	2	6	3.8	1.1	5.5	2.7
	Distal	0	0	0	1	4	5	4.2	0.3	4.7	3.8
Total		0	0	5	5	11	21	-	-	-	-

Table 7b: Number and dimension of isthmus width measurements in mesial and distal of <u>failed</u> premolars and molars for Shell Crowns (N=8)

Tooth	Cavity Site	<1 mm	1-1.9 mm	2-2.9 mm	3-3.9 mm	≥4 mm	Total	Mean	SD	Max.	Min.
Premolar	Mesial	-	-	-	-	-	-	-	-	-	-
	Distal	-	-	-	-	-	-	-	-	-	-
Molar	Mesial	0	0	2	1	2	5	3.4	0.8	4.3	2.5
	Distal	0	0	0	0	3	3	5.7	0.4	6.2	5.5
Total		0	0	2	1	5	8	-	-	-	-

Table 8a: Number and dimension of isthmus width measurements in mesial and distal of premolars and molars for surviving Onlays (N=38)

Tooth	Cavity Site	<1 mm	1-1.9 mm	2-2.9 mm	3-3.9 mm	≥4 mm	Total	Mean	SD	Max.	Min.
Premolar	Mesial	0	1	0	2	1	4	3.1	1.5	4.9	1.2
	Distal	0	0	1	0	2	3	3.7	1.3	4.7	2.2
Molar	Mesial	1	0	7	6	3	17	3.1	1.2	5.4	0.5
	Distal	0	1	1	7	5	14	3.8	1.1	5.2	1.7
Total		1	2	9	15	11	38	-	-	-	-

Table 8b: Number and dimension of isthmus width measurements in mesial and distal of premolars and molars for failed Onlays (N=16)

Tooth	Cavity Site	<1 mm	1-1.9 mm	2-2.9 mm	3-3.9 mm	≥4 mm	Total	Mean	SD	Max.	Min.
Premolar	Mesial	-	-	-	-	-	-	-	-	-	-
	Distal	-	-	-	-	-	-	-	-	-	-
Molar	Mesial	0	2	1	1	5	9	3.3	1.2	4.7	1.0
	Distal	0	0	2	1	4	7	4.3	1.4	6.0	2.4
Total		0	2	3	2	9	16	-	-	-	-

Table 9a: Number and dimension of proximal width measurements in mesial and distal of surviving Shell Crowns (N= 14)

Tooth	Cavity Site	3-3.9 mm	4-4.9 mm	5-5.9 mm	≥6 mm	Total	Mean	SD	Max.	Min.
Premolar	Mesial	1	0	1	0	2	4.6	1.3	5.5	3.7
	Distal	2	0	1	0	3	4.4	1.3	5.9	3.6
Molar	Mesial	1	3	0	1	5	4.5	0.9	6.0	3.5
	Distal	0	2	0	2	4	5.6	1.3	6.8	4.1
Total		4	5	2	3	14	-	-	-	-

Table 9b: Number and dimension of proximal width measurements in mesial and distal of failed Shell Crowns (N= 4)

Tooth	Cavity Site	3-3.9 mm	4-4.9 mm	5-5.9 mm	≥6 mm	Total	Mean	SD	Max.	Min.
Premolar	Mesial	-	-	-	-	-	-	-	-	-
	Distal	-	-	-	-	-	-	-	-	-
Molar	Mesial	1	1	0	0	2	4.2	1.0	4.9	3.5
	Distal	0	0	2	0	2	5.4	0.3	5.6	5.1
Total		1	1	2	0	4	-	-	-	-

Table 10a: Number and dimension of proximal width measurements in mesial and distal of <u>surviving</u> Onlays (N= 28)

Tooth	Cavity Site	3-3.9 mm	4-4.9 mm	5-5.9 mm	≥6 mm	Total	Mean	SD	Max.	Min.
Premolar	Mesial	1	3	1	0	5	4.8	0.4	5.4	4.4
	Distal	0	1	4	1	6	5.4	0.8	6.7	4.3
Molar	Mesial	1	6	4	1	12	4.8	1.1	6.8	2.1
	Distal	0	2	2	1	5	4.9	1.1	6.4	3.1
Total		2	12	11	3	28	-	-	-	-

Table 10b: Number and dimension of proximal width measurements in mesial and distal of <u>failed</u> Onlays (N= 13)

Tooth	Cavity Site	3-3.9 mm	4-4.9 mm	5-5.9 mm	≥6 mm	Total	Mean	SD	Max.	Min.
Premolar	Mesial	-	-	-	-	-	-	-	-	-
	Distal	-	-	-	-	-	-	-	-	-
Molar	Mesial	1	2	3	1	7	5.1	0.8	6.2	3.8
	Distal	1	2	2	1	6	4.9	0.9	6.1	3.5
Total		2	4	5	2	13	-	-	-	-

Table 11a: Number and dimension of height of axial wall measurements in mesial and distal of surviving Shell Crowns (N= 11)

Tooth	Cavity Site	1-1.9 mm	2-2.9 mm	3-3.9 mm	≥4 mm	Total	Mean	SD	Max.	Min.
Premolar	Mesial	1	1	0	0	-	-	-	-	-
	Distal	0	1	0	0	-	-	-	-	-
Molar	Mesial	1	1	3	0	5	2.8	1.0	3.7	1.5
	Distal	0	2	0	1	3	3.4	1.2	4.8	2.6
Total		2	5	3	1	11	-	-	-	-

Table 11b: Number and dimension of height of axial wall measurements in mesial and distal of failed Shell Crowns (N= 6)

Tooth	Cavity Site	<1 mm	1-1.9 mm	2-2.9 mm	3-3.9 mm	≥4 mm	Total	Mean	SD	Max.	Min.
Premolar	Mesial	-	-	-	-	-	-	-	-	-	-
	Distal	-	-	-	-	-	-	-	-	-	-
Molar	Mesial	0	1	3	0	0	4	2.3	0.8	2.9	1.2
	Distal	0	0	1	1	0	2	3.2	0.8	3.8	2.7
Total		0	1	4	1	0	6	-	-	-	-

Table 12a: Number and dimension of height of axial wall measurements in mesial and distal of <u>surviving</u> Onlays (N= 25)

Tooth	Cavity Site	1-1.9 mm	2-2.9 mm	3-3.9 mm	≥4 mm	Total	Mean	SD	Max.	Min.
Premolar	Mesial	1	2	1	0	4	2.3	0.6	3.3	1.8
	Distal	0	5	2	0	7	2.6	0.6	3.6	2.0
Molar	Mesial	2	4	2	1	9	2.7	1.1	4.9	1.3
	Distal	0	3	2	0	5	3.0	0.5	3.7	2.5
Total		3	14	7	1	25	-	-	-	-

Table 12b: Number and dimension of height of axial wall measurements in mesial and distal of <u>failed</u> Onlays (N= 15)

Tooth	Cavity Site	<1 mm	1-1.9 mm	2-2.9 mm	3-3.9 mm	≥4 mm	Total	Mean	SD	Max.	Min.
Premolar	Mesial	-	-	-	-	-	-	-	-	-	-
	Distal	-	-	-	-	-	-	-	-	-	-
Molar	Mesial	0	1	3	4	0	8	2.7	0.7	3.4	1.5
	Distal	1	0	2	2	2	7	3.0	1.2	4.3	0.9
Total		1	1	5	6	2	15	-	-	-	-

Table 13a: Number and dimension of depth of occlusal floor measurements in mesial and distal of molar and premolar teeth in surviving Shell Crowns without metal reinforcement (N= 15)

Tooth	Cavity Site	<1 mm	1-1.9 mm	2-2.9 mm	3-3.9 mm	4-4.9 mm	≥5 mm	Total	Mean	SD	Max.	Min.
Premolar	Mesial	1	0	4	0	1	0	6	2.8	1.6	5.7	0.9
	Distal	-	-	-	-	-	-	-	-	-	-	-
Molar	Mesial	0	0	2	1	0	2	5	3.9	1.3	6.1	2.1
	Distal	0	1	1	1	1	0	4	3.03	1.02	4.2	1.9
Total		1	1	7	2	2	2	15	-	-	-	-

Table 13b: Number and dimension of depth of occlusal floor measurements in mesial and distal of molar and premolar teeth in surviving Shell Crowns with metal reinforcement (N= 21)

Tooth	Cavity Site	<1 mm	1-1.9 mm	2-2.9 mm	3-3.9 mm	4-4.9 mm	≥5 mm	Total	Mean	SD	Max.	Min.
Premolar	Mesial	0	2	8	5	0	0	15	2.5	0.6	3.3	1.1
	Distal	-	-	-	-	-	-	-	-	-	-	-
Molar	Mesial	0	0	2	1	0	0	3	3	0.2	3.2	2.9
	Distal	0	0	2	1	0	0	3	2.1	0.4	3.2	2.4
Total		0	2	12	7	0	0	21	-	-	-	-

Table 13c: Number and dimension of depth of occlusal floor measurements in mesial and distal of posterior teeth in failed Shell Crowns with (N=4)and without(N=9)metal reinforcement

Tooth	Cavity Site	<1 mm	1-1.9 mm	2-2.9 mm	3-3.9 mm	4-4.9 mm	≥5 mm	Total	Mean	SD	Max.	Min.
With Metal	Mesial	0	0	0	1	0	1	2	4.8	2.5	6.6	3.0
	Distal	0	0	0	1	0	1	2	4.7	1.9	6.0	3.3
Without Metal	Mesial	0	0	1	3	0	1	5	3.5	1.0	5.1	2.3
	Distal	0	1	1	1	0	1	4	3.0	1.0	4.1	1.8
Total		0	1	2	6	0	4	13	-	-	-	-

Table 14a: Number and dimension of depth of occlusal floor measurements in mesial and distal of molar and premolar teeth in surviving Onlays without metal reinforcement (N= 47)

Tooth	Cavity Site	<1 mm	1-1.9 mm	2-2.9 mm	3-3.9 mm	4-4.9 mm	≥5 mm	Total	Mean	SD	Max.	Min.
Premolar	Mesial	2	1	5	1	1	0	10	2.4	1.1	4.5	0.6
	Distal	-	-	-	-	-	-	-	-	-	-	-
Molar	Mesial	1	2	6	2	6	1	18	3.2	1.4	5.2	0.7
	Distal	3	1	3	7	4	1	19	3.1	1.4	5.5	0.7
Total		6	4	14	10	11	2	47	-	-	-	-

Table 14b: Number and dimension of depth of occlusal floor measurements in mesial and distal of molar and premolar teeth in surviving Onlays with metal reinforcement (N= 13)

Tooth	Cavity Site	<1 mm	1-1.9 mm	2-2.9 mm	3-3.9 mm	4-4.9 mm	≥5 mm	Total	Mean	SD	Max.	Min.
Premolar	Mesial	0	0	2	1	0	0	3	2.5	0.8	3.4	2.0
	Distal	-	-	-	-	-	-	-	-	-	-	-
Molar	Mesial	0	1	1	1	2	0	5	3.2	1.5	4.8	1.4
	Distal	0	0	4	1	0	0	5	2.3	0.5	3.2	2.0
Total		0	1	7	3	2	0	13	-	-	-	-

Table 14c: Number and dimension of depth of occlusal floor measurements in mesial and distal of posterior teeth in failed Onlays with (N=7) and without (N=13) metal reinforcement

Tooth	Cavity Site	<1 mm	1-1.9 mm	2-2.9 mm	3-3.9 mm	4-4.9 mm	≥5 mm	Total	Mean	SD	Max.	Min.
With Metal	Mesial	0	1	1	1	1	0	4	3.0	1.1	4.3	1.9
	Distal	0	3	0	0	0	0	3	2.3	0.5	2.9	2.0
Without Metal	Mesial	0	2	6	0	0	0	8	2.1	0.3	2.4	1.5
	Distal	0	0	3	2	0	0	5	2.6	0.4	3.2	2.2
Total		0	6	10	3	1	0	20	-	-	-	-

Table 15a: Number and dimension of cusp reduction measurements in mesial and distal of molar and premolar teeth in surviving Shell Crowns without metal reinforcement (N=15)

Tooth	Cavity Site	<1 mm	1-1.9 mm	2-2.9 mm	3-3.9 mm	4-4.9 mm	Total	Mean	SD	Max.	Min.
Premolar	Mesial	2	1	1	2	0	6	1.9	1.3	3.4	0.5
	Distal	-	-	-	-	-	-	-	-	-	-
Molar	Mesial	0	4	1	0	0	5	1.7	0.5	2.3	1.2
	Distal	0	3	1	0	0	4	1.7	0.3	2.2	1.4
Total		2	8	3	2	0	15	-	-	-	-

Table 15b: Number and dimension of cusp reduction measurements in mesial and distal of molar and premolar teeth in surviving Shell Crowns with metal reinforcement (N=23)

Tooth	Cavity Site	<1 mm	1-1.9 mm	2-2.9 mm	3-3.9 mm	4-4.9 mm	Total	Mean	SD	Max.	Min.
Premolar	Mesial	2	6	3	4	0	15	2	1.0	3.5	0.7
	Distal	-	-	-	-	-	-	-	-	-	-
Molar	Mesial	0	1	3	0	0	4	2.2	0.6	2.9	1.5
	Distal	0	1	0	2	1	4	2.9	1.1	4.0	1.4
Total		2	8	6	6	1	23	-	-	-	-

Table 15c: Number and dimension of cusp reduction measurements in mesial and distal of posterior teeth in failed Shell Crowns with (N=4) and without (N=9) metal reinforcement

Tooth	Cavity Site	<1 mm	1-1.9 mm	2-2.9 mm	3-3.9 mm	4-4.9 mm	Total	Mean	SD	Max.	Min.
With Metal	Mesial	0	0	2	0	0	2	2.3	0.2	2.4	2.1
	Distal	0	0	0	2	0	2	3.2	0.2	3.3	1.3
Without Metal	Mesial	0	2	3	0	0	5	2.2	0.7	2.8	1.3
	Distal	0	2	2	0	0	4	2.1	0.4	2.5	1.5
Total		0	4	7	2	0	13	-	-	-	-

Table 16a: Number and dimension of cusp reduction measurements in mesial and distal of molar and premolar teeth in surviving Onlays without metal reinforcement(N=44)

Tooth	Cavity Site	<1 mm	1-1.9 mm	2-2.9 mm	3-3.9 mm	4-4.9 mm	Total	Mean	SD	Max.	Min.
Premolar	Mesial	5	3	1	1	0	10	1.2	1.1	3.9	0.4
	Distal	-	-	-	-	-	-	-	-	-	-
Molar	Mesial	2	6	8	2	0	18	2.0	0.8	3.6	0.7
	Distal	4	5	6	1	0	16	1.7	1.0	3.4	0.3
Total		11	14	15	4	0	44	-	-	-	-

Table 16b: Number and dimension of cusp reduction measurements in mesial and distal of molar and premolar teeth in surviving Onlays with metal reinforcement(N=12)

Tooth	Cavity Site	<1 mm	1-1.9 mm	2-2.9 mm	3-3.9 mm	4-4.9 mm	Total	Mean	SD	Max.	Min.
Premolar	Mesial	1	2	0	0	0	3	1.3	0.9	1.8	0.4
	Distal	-	-	-	-	-	-	-	-	-	
Molar	Mesial	0	1	3	1	0	5	2.6	0.8	3.7	1.5
	Distal	1	1	1	1	0	4	2.1	0.9	3.1	0.9
Total		2	4	4	2	0	12	-	-	-	-

Table 16c: Number and dimension of cusp reduction measurements in mesial and distal of posterior teeth in failed Onlays with (N=7) and without (N=13) metal reinforcement

Tooth	Cavity Site	<1 mm	1-1.9 mm	2-2.9 mm	3-3.9 mm	4-4.9 mm	Total	Mean	SD	Max.	Min.
With Metal	Mesial	1	2	1	0	0	4	2.0	0.6	3.3	1.4
	Distal	0	2	1	0	0	3	2.04	0.8	3.1	1.2
Without Metal	Mesial	0	4	3	1	0	8	1.8	0.8	2.8	0.9
	Distal	0	2	2	1	0	5	1.6	0.5	2.0	1.1
Total		1	10	7	2	0	20	-	-	-	-

Table 17a: Characteristics of tooth preparation in <u>surviving</u> Shell Crown restorations (premolar= 25, molar= 10)

Tooth	Cavity Site	Gingival margin in dentine	Margins bevelled gingivally	Opposing tooth contact at Margins	Angular cavosurface margins	Sharp internal line/point angle	Retention grooves	Prep. taper<20	Proximal Box	Occlusal Box	Metal Reinforcement
Premolar	Mesial %	8	8	0	0	0	4	80			
	Distal %	8	4	0	0	0	0	80	16	12	60
Molar	Mesial %	10	20	0	0	0	0	20			
	Distal %	10	0	10	0	0	20	30	50	60	50
Average		9	7	1.4	0	0	4.3	64	26	26	57

Table 17b: Characteristics of tooth preparation in <u>failed</u> Shell Crown restorations (premolar= 7, molar= 8)

Tooth	Cavity Site	Gingival margin in dentine	Margins bevelled gingivally	Opposing tooth contact at Margins	Angular cavosurface margins	Sharp internal line/point angle	Retention grooves	Prep. taper<20	Proximal Box	Occlusal Box	Metal Reinforcement
Premolar	Mesial %	0	29	0	0	0	0	71			
	Distal %	0	0	0	0	0	20	71	14	0	43
Molar	Mesial %	0	0	0	0	0	25	13			
	Distal %	0	0	0	0	0	0	25	50	75	25
Average		0	13	0	0	0	13	43	33	40	33

Table 18a: Characteristics of tooth preparation in surviving Onlay restorations (premolar= 17, molar= 26)

Tooth	Cavity Site	Gingival margin in dentine	Margins bevelled gingivally	Opposing tooth contact at Margins	Angular cavosurface margins	Sharp internal line/point angle	Retention grooves	Prep. taper<20	Proximal Box	Occlusal Box	Metal Reinforcement
Premolar	Mesial %	0	0	6	0	0	6	24			
	Distal %	0	0	12	0	0	6	18	41	47	18
Molar	Mesial %	8	23	15	0	0	4	19			
	Distal %	8	15	4	0	0	8	12	46	81	19
Average		4.7	12	9.3	0	0	5.8	17	44	67	19

Table 18b: Characteristics of tooth preparation in failed Onlay restorations (premolar= 4, molar= 16)

Tooth	Cavity Site	Gingival margin in dentine	Margins bevelled gingivally	Opposing tooth contact	Angular cavosurface margins at Margins	Sharp internal line/point angle	Retention grooves	Prep. taper<20	Proximal Box	Occlusal Box	Metal Reinforcement
Premolar	Mesial %	0	0	0	0	0	0	75			
	Distal %	0	50	0	0	0	0	100	100	75	0
Molar	Mesial %	0	25	0	0	0	25	38			
	Distal %	0	19	0	0	0	13	31	69	75	25
Average		0	23	0	0	0	15	45	75	75	20

Table 19: Percentage of preparation taper in premolars and molars in surviving Shell Crown (N=64) and Onlay (N=71) restorations

Sites	<10°	10-20°	21-40°	41-60°	61-80°	>80°
Shell Crown Premolar	11.9	16.3	4.4	1.5	0.0	0.0
Shell Crown Molar	0.7	3.7	3.7	1.5	1.5	2.2
Total	12.6	20	8.1	3	1.5	2.2
Onlay Premolar	1.5	3.7	9.6	1.5	1.5	0.0
Onlay Molar	0.7	5.2	20.7	3.7	0.7	3.7
Total	2.2	8.9	30.3	5.2	2.2	3.7

Table 20: Percentage of preparation taper in premolars and molars in failed Shell Crown (N=32) and Onlay (N=38) restorations

Sites	<10°	10-20°	21-40°	41-60°	61-80°	>80°
Shell Crown Premolar	7.1	11.4	4.3	0.0	0.0	0.0
Shell Crown Molar	1.4	4.3	7.1	4.3	0.0	5.7
Total	8.5	15.7	11.4	4.3	0	5.7
Onlay Premolar	1.4	5.7	1.4	0.0	0.0	0.0
Onlay Molar	4.3	14.3	5.7	10.0	0.0	11.4
Total	5.7	20	7.1	10	0	11.4

Appendix IV

RESULTS OF RESTORATION FAILURES (Section 5.2)

Table 1: Distribution of restorations in male and female patients by age groups (N = 222)

Age Groups	Female (%)	Male (%)	Total (%)	Female	Male	Total
10-20	10	5	15	22	10	32
21-30	13	5	18	28	12	40
31-40	16	10	26	36	23	59
41-50	14	10	24	32	21	53
>50	10	7	17	22	16	38
Total	63	37	100	140	82	222

$\chi^2 = 1.977$, df = 4, p = 0.74

Table 2a: Distribution of restorations in male and female patients in different age groups by operator (N=222)

Age Groups	Operator 1		Operator 2		Total
	Female	Male	Female	Male	
10-20	9	9	13	1	32
21-30	12	4	16	8	40
31-40	19	12	17	11	59
41-50	14	12	18	9	53
>50	6	10	16	6	38
Total	60	47	80	35	222

$\chi^2 = 5.232$, df = 4, p = 0.26 $\chi^2 = 4.930$, df = 4, p = 0.29

Table 2b: Distribution of restorations in different age groups (N=536)

Age Groups	Veneer	Incisal Veneer	Shell Crown	Onlay	Inlay	Chip	Fix-Fix Bridge	Cantilever Bridge	Total
10-20	3	16	30	0	1	2	7	19	78
21-30	16	0	40	7	1	0	6	6	76
31-40	10	3	43	29	2	0	8	11	106
41-50	8	20	77	39	5	9	4	6	168
>50	27	7	39	22	0	4	2	7	108
Total	64	46	229	97	9	15	27	49	536

Table 3: Distribution of restoration types in male and female patients (N=536)

Gender	Veneer	Incisal Veneer	Shell Crown	Onlay	Inlay	Chip	Fix-Fix Bridge	Cantilever Bridge	Total
Female	50	29	142	46	7	4	18	30	326
Male	14	17	87	51	2	11	9	19	210
Total	64	46	229	97	9	15	27	49	536

$\chi^2 = 24.400$, df = 7, p = 0.001 (sig. diff.)

Table 4: Distribution of restorations in anterior and posterior regions of maxilla and mandible (N=536)

Arch		Veneer	Incisal Veneer	Shell Crown	Onlay	Inlay	Chip	Fix-Fix Bridge	Cantilever Bridge	Total
Maxilla	Ant.	43	33	113	3	0	8	20	40	260
	Post.	6	1	35	46	7	0	1	6	102
Mandible	Ant.	15	12	21	1	0	7	3	2	61
	Post.	0	0	60	47	2	0	3	1	113
Total		64	46	229	97	9	15	27	49	536

Table 5: Distribution of restorations by metal reinforcement (N=536)

Restoration Type	With Metal(%)	Without Metal (%)	Total (%)	With Metal (no.)	Without Metal (no.)	Total (no.)
Veneer	0	12	12	0	64	64
Incisal Veneer	0	8	8	0	46	46
Shell Crown	12	31	43	62	167	229
Onlay	3.2	15	18.2	19	78	97
Inlay	0.6	1	1.6	3	6	9
Chip	0	3	3	0	15	15
Fix-Fix Bridge	5	0	5	27	0	27
Cantilever Bridge	9	0.2	9.2	48	1	49
Total	30.8	70.2	100	159	377	536

Table 6: Distribution of retainers in fixed-fixed and cantilever bridges (N=105)

Bridge Type	Anterior					Posterior					Total
	Veneer	Incisal Veneer	Shell Crown	Onlay	Inlay	Veneer	Incisal Veneer	Shell Crown	Onlay	Inlay	
Fix-Fix Bridge	12	8	28	0	0	0	0	5	2	1	56
Cantilever Bridge	11	2	29	0	0	0	0	6	1	0	49
Total	23	10	57	0	0	0	0	11	3	1	105

Table 7: Distribution of restorations in maxilla and mandible for operator 1 (+with metal, - without metal)(N=320)

Arch		Veneer	Incisal Veneer	Shell Cr.+	Shell Cr.-	Onlay+	Onlay-	Inlay+	Inlay-	Chip	Fix-Fix Bridge	Cantilever Bridge	Total
Maxilla	Ant.	32	10	6	53	0	3	0	0	8	6	14	132
	Post.	6	1	7	5	11	25	2	3	0	1	2	63
Mandible	Ant.	15	11	2	17	0	1	0	0	6	1	1	54
	Post.	0	0	18	16	3	31	1	0	0	2	0	71
Total		53	22	33	91	14	60	3	3	14	10	17	320

Table 8: Distribution of restorations in maxilla and mandible for operator 2 (+with metal, - without metal)(N=216)

Arch		Veneer	Incisal Veneer	Shell Cr.+	Shell Cr.-	Onlay+	Onlay-	Inlay+	Inlay-	Chip	Fix-Fix Bridge	Cantilever Bridge+	Cantilever Bridge-	Total
Maxilla	Ant.	11	17	9	45	0	0	0	0	0	14	25	1	122
	Post.	0	0	10	11	1	9	0	2	0	0	4	0	37
Mandible	Ant.	0	7	0	2	0	0	0	0	1	2	1	0	13
	Post.	0	0	10	18	4	9	0	1	0	1	1	0	44
Total		11	24	29	76	5	18	0	3	1	17	31	1	216

Table 9a: Reasons for placement of restorations relating to tooth problems in male and female patients (N=497)

Gender	Abutment	Missing	Wear	Malocclusion	Discoloration	Fracture	RCF	Defect	Sensitive	Total
Female	69	50	38	34	53	37	5	6	3	295
Male	32	28	56	48	7	22	4	1	4	202
Total	101	78	94	82	60	59	9	7	7	497

$\chi^2 = 52.950$, df = 8, $p < 0.001$ (sig. diff.)

Table9b: Reasons for placement of different restorations relating to tooth problems by restoration type (N=497)

Restoration Type	Abutment	Missing	Wear	Fracture	Malocclusion	Discoloration	RCF	Defect	Sensitive	Total
Veneer	23	0	19	2	5	21	0	2	0	49
Incisal Veneer	10	0	25	0	11	7	0	0	0	43
Shell Crown	68	0	19	30	49	30	8	4	2	143
Onlay	3	0	27	22	16	2	1	1	3	72
Inlay	1	0	0	1	0	0	0	0	0	1
Chip	0	0	4	4	1	0	0	0	2	11
Fix-Fix Bridge	-	29	0	0	0	0	0	0	0	85
Cantilever Bridge	-	49	0	0	0	0	0	0	0	98
Total	105	78	94	59	82	60	9	7	7	497

Table 10a: Reasons for placement of restorations relating to previous restoration problems in male and female patients (N=149)

Gender	Discol./Poor shape	Wear	Fracture	Malocclusion	Microleakage/ Sensitivity	Hg scare	Caries	Contacts/Food impaction	Loss	Total
Female	39	13	25	2	6	13	4	1	3	106
Male	6	0	19	0	9	0	3	4	2	43
Total	45	13	44	2	15	13	7	5	5	149

$\chi^2 = 35.463$, df = 8, $p < 0.001$ (sig. diff.)

Table 10b: Reasons for placement of different restorations relating to previous restoration problems by restoration type (N=149)

Restoration Type	Discol./Poor shape	Wear	Fracture	Malocclusion	Microleakage /Sensitivity	Hg scare	Caries	Contacts/Food impaction	Loss	Total
Veneer	5	0	10	0	0	0	0	0	0	15
Incisal Veneer	2	0	0	0	0	0	0	0	1	3
Shell Crown	37	8	20	2	11	5	4	2	1	90
Onlay	1	3	9	0	2	5	3	3	0	26
Inlay	0	2	1	0	2	3	0	0	0	8
Chip	0	0	2	0	0	0	0	0	2	4
Fix-Fix Bridge	0	0	2	0	0	0	0	0	1	3
Cantilever Bridge	0	0	0	0	0	0	0	0	0	0
Total	45	13	44	2	15	13	7	5	5	149

Table 11: Failure modes for different restorations (+ with metal, - without metal reinforcement)(N=123)

Restoration	Debond	Pulpitis	Bulk Fracture	Chip Fracture	Microfracture	Connector Fracture	Colour Mismatch	Food Impaction	2° Caries	Apparen t	Total (%)
Veneer	1	0	6	0	0	0	1	0	0	1	9 (14)
Inc. Veneer	1	0	0	0	0	0	0	0	0	0	1 (2)
Shell Cr.-	3	6	16	4	0	0	2	1	0	4	36 (22)
Shell Cr.+	3	2	0	1	3	0	0	0	0	0	9 (15)
Onlay-	3	6	13	4	3	0	0	0	0	0	29 (37)
Onlay+	0	0	5	0	0	0	1	0	0	0	6 (32)
Inlay+	0	0	0	0	0	0	0	0	0	0	0 (0)
Inlay-	0	0	0	0	0	0	0	0	0	0	0 (0)
Fix-Fix Bridge	1	0	11	2	0	3	1	0	0	1	19 (70)
Cantilever Bridge	3	1	3	1	0	0	0	0	0	2	10 (20)
Chip	0	0	2	2	0	0	0	0	0	0	4 (27)
Total (%)	15 (12)	15 (12)	56 (46)	14 (11)	6 (5)	3 (2)	5 (4)	1 (1)	0 (0)	8 (7)	123
Total %	2.8	2.8	10.4	2.6	1.1	0.6	1.0	0.1	0.0	1.5	23

Table 12: Numbers and percentages of failed restorations for anterior and posterior regions (N=116)

Arch		Veneer	Incisal Veneer	Shell Crown+	Shell Crown-	Onlay+	Onlay-	Chip	Fix-Fix Bridge	Cantilever Bridge	Total
Maxilla	Ant. (%)	4 (9)	0 (0)	1 (7)	12 (12)	0 (0)	0 (0)	4 (50)	14 (35)	7 (35)	42
	Post. (%)	1 (17)	0 (0)	1 (6)	4 (25)	2 (17)	15 (19)	0	0 (0)	1 (100)	24
Mandible	Ant. (%)	4 (27)	1 (33)	2 (100)	3 (16)	0 (0)	0 (0)	0	2 (100)	1 (33)	13
	Post. (%)	0 (0)	0 (0)	5 (18)	16 (47)	3 (43)	12 (30)	0	1 (100)	0 (0)	37
Total		9	1	9	35	5	27	4	17	9	116

Table 13: Failures for each type of retainer in fixed-fixed and cantilever bridges (N=41)

Bridge Type	Anterior					Posterior					Total
	Veneer	Incisal Veneer	Shell Crown	Onlay	Inlay	Veneer	Incisal Veneer	Shell Crown	Onlay	Inlay	
Fix-Fix Bridge	8	7	15	0	0	0	0	2	0	0	32
Cantilever Bridge	2	0	6	0	0	0	0	1	0	0	9
Total (%)	10 (43)	7 (70)	21 (37)	0	0	0	0	3 (27)	0 (0)	0 (0)	41 (39)

Table 14: Failure modes for different age groups (N=123)

Failure Mode	10-20 Years	21-30 Years	31-40 Years	41-50 Years	51+ Years	Total
Debonding	2	0	6	1	6	15
Bulk Fracture	2	6	17	16	15	56
Chip Fracture	3	1	1	7	2	14
Connector Fracture	1	1	0	0	1	3
Microfracture	0	0	2	1	3	6
Colour Mismatch	2	0	1	2	0	5
Pulpitis	0	0	9	4	2	15
Food Impaction	0	0	0	0	1	1
Apparent Failure	5	1	2	0	0	8
Total (%)	15 (19)	9 (12)	38 (36)	31 (18)	30 (28)	123

Table 15: Failure modes for operator 1 (N=70)

Restoration Type	Debonding	Bulk Fracture	Chip Fracture	Connector Fracture	Micro-fracture	Colour Mismatch	Pulpitis	Food Impaction	Apparent Failure	Total (%)
Veneer	1	6	0	0	0	1	0	0	1	9 (17)
Incisal Veneer	0	0	0	0	0	0	0	0	0	0 (0)
Shell Crown	6	6	3	0	3	2	0	1	4	25 (20)
Onlay	2	13	2	0	3	1	3	0	0	24 (32)
Inlay	0	0	0	0	0	0	0	0	0	0 (0)
Chip	0	2	2	0	0	0	0	0	0	4 (29)
Fix-Fix Bridge	0	3	1	1	0	1	0	0	0	6 (60)
Cantilever Bridge	0	0	1	0	0	0	0	0	1	2 (12)
Total (%)	9 (13)	30 (43)	9 (13)	1 (1)	6 (9)	5 (7)	3 (4)	1 (1)	6 (9)	70 (22)

Table 16: Failure modes for operator 2 (N=53)

Restoration Type	Debonding	Bulk Fracture	Chip Fracture	Connector Fracture	Micro-fracture	Colour Mismatch	Pulpitis	Food Impaction	Apparent Failure	Total (%)
Veneer	0	0	0	0	0	0	0	0	0	0 (0)
Incisal Veneer	1	0	0	0	0	0	0	0	0	1 (5)
Shell Crown	0	10	2	0	0	0	8	0	0	3 (3)
Onlay	1	5	2	0	0	0	3	0	0	11 (48)
Inlay	0	0	0	0	0	0	0	0	0	0 (0)
Chip	0	0	0	0	0	0	0	0	0	0 (0)
Fix-Fix Bridge	1	8	1	2	0	0	0	0	1	13(71)
Cantilever Bridge	3	3	0	0	0	0	1	0	1	8 (25)
Total(%)	6 (11)	26 (49)	5 (9)	2 (4)	0 (0)	0 (0)	12 (23)	0 (0)	2 (4)	53 (25)

Table 17a: Number of restorations placed in bruxer patients (N=63)

Restoration Type	Anterior	Posterior	Total
Veneer	4	0	4
Incisal Veneer	6	0	6
Shell Crown+	0	3	3
Shell Crown -	0	16	16
Onlay+	0	3	3
Onlay-	1	20	21
Inlay+	0	0	0
Inlay-	0	2	2
Chip	6	0	6
Fix-Fix Bridge	0	0	0
Cantilever Bridge	2	0	2
Total	19	44	63

Table 17b: Failure modes for bruxers and nonbruxers (N=123)

Failure Mode	Bruxers (%)	Nonbruxers (%)	Total (No)
Debonding	1 (2)	14 (3)	15
Bulk Fracture	9(14)	47 (9)	56
Chip Fracture	3 (5)	11 (2)	14
Connector Frac.	0 (0)	3 (1)	3
Microfracture	3 (5)	3 (1)	6
Colour Mismatch	0 (0)	5 (1)	5
Pulpitis	2 (3)	13 (3)	15
Food Impaction	0 (0)	1 (0.2)	1
Apparent Failure	1 (2)	7 (1)	8
Total (%)	19 (30)	104 (22)	123

Table 17c: Failure modes for different restorations in bruxer patients (A: anterior, P: posterior) (N=19)

Failure Mode	Veneer	Incisal Veneer	Shell Crown+	Shell Crown-	Onlay+	Onlay-	Chip	Fix-Fix Bridge	Cantilever Bridge	Total
Debonding	-	-	-	-	-	1P	-	-	-	1
Bulk Fracture	1A	-	-	1P	-	5P	2A	-	-	9
Chip Fracture	-	-	-	2P	-	-	1A	-	-	3
Connector Frac.	-	-	-	-	-	-	-	-	-	0
Microfracture	-	-	-	-	-	3P	-	-	-	3
Pulpitis	-	-	-	2P	-	-	-	-	-	2
Total (%)	1 (2)	0 (0)	0 (0)	5 (8)	0 (0)	9 (14)	3 (5)	0 (0)	0 (0)	18 (30)

Table 17d: Longevity of the restorations before they failed.

Patients	Average Longevity (mth)	Minimum (day)	Maximum (mth)
Bruxers	22.38	15	65.2
Non-Bruxers	22.11	1	78.1

Table 18: Different bases used with different restorations (N=565)

Restoration Type	None	GIC	Other	Total
Veneer	61	3	0	64
Incisal Veneer	40	6	0	46
Shell Crown	133	87	9	229
Onlay	17	79	1	97
Inlay	2	7	0	9
Chip	14	1	0	15
Fix-Fix Bridge	41	13	2	56
Cantilever Bridge	40	6	3	49
Total (%)	348 (61)	202 (36)	15 (3)	565

Table 19: Different bases used by operator 1 (N=331)

Restoration Type	None	GIC	Other	Total
Veneer	51	2	0	53
Incisal Veneer	20	3	0	23
Shell Crown	84	40	0	124
Onlay	16	58	0	74
Inlay	1	5	0	6
Chip	13	1	0	14
Fix-Fix Bridge	10	10	0	20
Cantilever Bridge	15	2	0	17
Total	210	121	0	331

Table 20: Different bases used by operator 2 (N=234)

Restoration Type	None	GIC	Other	Total
Veneer	10	1	0	11
Incisal Veneer	20	3	0	23
Shell Crown	49	47	9	105
Onlay	1	21	1	23
Inlay	1	2	0	3
Chip	1	0	0	1
Fix-Fix Bridge	31	3	2	36
Cantilever Bridge	25	4	3	32
Total	138	81	15	234

Table 21: Failure modes with different bases for operator 1 (N=70)

Failure Mode	None	GIC	Other	Total
Debonding	7	2	0	9
Bulk Fracture	18	12	0	30
Chip Fracture	5	4	0	9
Connector Frac.	1	0	0	1
Microfracture	2	4	0	6
Colour Mismatch	4	1	0	5
Pulpitis	1	2	0	3
Food Impaction	1	0	0	1
Apparent Failure	6	0	0	
Total (%)	45 (21)	25 (21)	0 (0)	70 (21)

Table 22: Failure modes with different bases for operator 2 (N=53)

Failure Mode	None	GIC	Other	Total
Debonding	4	1	1	6
Bulk Fracture	11	11	4	26
Chip Fracture	2	2	1	5
Connector Frac.	2	0	0	2
Microfracture	0	0	0	0
Colour Mismatch	0	0	0	0
Pulpitis	2	10	0	12
Food Impaction	0	0	0	0
Apparent Failure	2	0	0	2
Total (%)	23 (17)	24 (30)	6 (40)	53 (23)

Table 23: Postoperative sensitivity with different bases for operators 1 and 2 (N=35)

Restoration Type	Operator 1				Operator 2			
	None	GIC	Other	Total	None	GIC	Other	Total
Veneer	1	0	0	1	0	0	0	0
Incisal Veneer	0	0	0	0	0	0	0	0
Shell Crown	0	4	0	4	10	11	1	22
Onlay	1	6	0	7	0	9	0	9
Inlay	0	0	0	0	0	1	0	1
Chip	0	0	0	0	0	0	0	0
Fix-Fix Bridge	0	5	0	5	0	0	0	0
Cantilever Bridge	0	0	0	0	1	1	1	3
Total	2	15	0	17	11	22	2	35

Table 24: Numbers with postoperative sensitivity, and postoperative sensitivity leading to pulpitis in different restorations

Sensitivity	Veneer	Incisal Veneer	Shell Crown	Onlay	Inlay	Chip	Fix-Fix Bridge	Cantilever Bridge	Total (%)
Post-operative Sensitivity (short-term)	1	0	26	16	1	0	5	3	52 (9)
Post-operative Sensitivity Leading to Pulpitis	0	0	8	6	0	0	0	1	15 (2.7)

Table 25: Types of cements used by operators (N=536)

Operator	Mirage	Insure	Ultra-Bond	Porcelite	Sono-Cem	Dicor	Other	Total
Operator 1	17	4	293	2	0	0	4	320
Operator 2	124	63	4	11	5	9	0	216
Total (%)	141 (26)	67 (13)	297 (55)	13 (2)	5 (1)	9 (2)	4 (1)	536

Table 26: Failure modes with different cements (N=123)

Failure Mode	Mirage	Insure	Ultra-Bond	Porcelite	Sono-Cem	Dicor	Other	Total
Debonding	4	0	9	0	1	1	0	15
Bulk Fracture	27	1	28	0	0	0	0	56
Chip Fracture	5	0	9	0	0	0	0	14
Connector Frac.	2	0	1	0	0	0	0	3
Microfracture	0	0	6	0	0	0	0	6
Colour Mismatch	0	0	5	0	0	0	0	5
Pulpitis	11	1	2	1	0	0	0	15
Food Impaction	0	0	1	0	0	0	0	1
Apparent Failure	2	0	5	1	0	0	0	8
Total (%)	51 (36)	2 (3)	66 (22)	2 (15)	1 (20)	1 (11)	0 (0)	123

Appendix V

LIFE TABLES ESTIMATES

1- Overall Total Restorations

Time Period (months)	Proportion Exposed (Total 514)	Proportion True Failure (Total 104)	Cumulative Proportion Surviving ± SE %
0-6	408.5	0.029	92.2 ± 1.25
6-12	370.5	0.029	89.5 ± 1.46
12-18	341.0	0.035	86.3 ± 1.67
18-24	311.5	0.028	83.8 ± 1.81
24-30	287.0	0.027	81.5 ± 1.94
30-36	263.0	0.019	79.9 ± 2.03
36-42	242.5	0.024	77.9 ± 2.13
42-48	209.0	0.019	76.5 ± 2.22
48-54	171.0	0.029	74.2 ± 2.37
54-60	130.0	0.030	71.9 ± 2.55
60-66	83.5	0.00	71.9 ± 2.55
66-72	47.5	0.00	71.9 ± 2.55
72-78	17.0	0.058	67.7 ± 4.76
78-84	1.0	0.00	67.7 ± 4.76

75th Quartile = 57.99 ± 6.19

2- Veneers without Incisal Coverage

Time Period (months)	Proportion Exposed (Total 64)	Proportion True Failure (Total 8)	Cumulative Proportion Surviving ± SE %
0-6	59.0	0.07	93.2 ± 3.27
6-12	52.0	0.00	93.2 ± 3.27
12-18	51.0	0.04	89.6 ± 4.04
18-24	46.5	0.00	89.6 ± 4.04
24-30	45.0	0.00	89.6 ± 4.04
30-36	45.0	0.022	87.6 ± 4.41
36-42	42.0	0.023	85.5 ± 4.77
42-48	38.0	0.00	85.5 ± 4.77
48-54	35.0	0.00	85.5 ± 4.77
54-60	30.5	0.00	85.5 ± 4.77
60-66	20.5	0.00	85.5 ± 4.77
66-72	12.0	0.00	85.5 ± 4.77
72-78	5.0	0.00	85.5 ± 4.77
78-84	5.0	0.00	-

75th Quartile = Not Provided

3- Veneers with Incisal Coverage

Time Period (months)	Proportion Exposed (Total 46)	Proportion True Failure (Total 1)	Cumulative Proportion Surviving ± SE %
0-6	33.0	0.00	100.0 ± 0.00
6-12	30.0	0.00	100.0 ± 0.00
12-18	27.0	0.00	100.0 ± 0.00
18-24	24.0	0.00	95.8 ± 4.08
24-30	22.0	0.042	95.8 ± 4.08
30-36	22.0	0.00	95.8 ± 4.08
36-42	22.0	0.00	95.8 ± 4.08
42-48	20.5	0.00	95.8 ± 4.08
48-54	19.0	0.00	95.8 ± 4.08
54-60	18.0	0.00	95.8 ± 4.08
60-66	13.0	0.00	95.8 ± 4.08
66-72	6.0	0.00	95.8 ± 4.08
72-78	1.5	0.00	95.8 ± 4.08
78-84	1.5	0.00	-

75th Quartile = Not Provided

4- Onlays without Metal Reinforcement

Time Period (months)	Proportion Exposed (Total 78)	Proportion True Failure (Total 27)	Cumulative Proportion Surviving ± SE %
0-6	72.0	0.04	90.8 ± 3.30
6-12	69.0	0.04	86.9 ± 3.86
12-18	65.0	0.06	81.6 ± 4.45
18-24	59.5	0.02	80.2 ± 4.59
24-30	56.5	0.07	74.5 ± 5.06
30-36	50.0	0.02	73.02 ± 5.18
36-42	47.0	0.00	73.02 ± 5.18
42-48	42.5	0.02	71.3 ± 5.33
48-54	36.0	0.06	67.3 ± 5.73
54-60	29.5	0.10	60.5 ± 6.36
60-66	21.0	0.00	60.5 ± 6.36
66-72	15.5	0.00	60.5 ± 6.36
72-78	7.5	0.13	52.4 ± 9.32
78-84	0.5	0.00	52.4 ± 9.32

75th Quartile = 35.48 ± 7.64

5- Onlays with Metal Reinforcement

Time Period (months)	Proportion Exposed (Total 19)	Proportion True Failure (Total 5)	Cumulative Proportion Surviving ± SE %
0-6	15.5	0.00	89.2 ± 7.22
6-12	15.0	0.07	83.2 ± 8.85
12-18	13.0	0.00	83.2 ± 8.85
18-24	12.0	0.00	83.24 ± 8.85
24-30	11.0	0.00	83.2 ± 8.85
30-36	10.0	0.10	74.9 ± 11.22
36-42	8.5	0.00	74.9 ± 11.22
42-48	6.0	0.17	62.4 ± 14.74
48-54	2.5	0.00	62.4 ± 14.74
54-60	1.0	0.00	62.4 ± 14.74
60-66	1.0	0.00	62.4 ± 14.74
66-72	-	-	-
72-78	-	-	-
78-84	-	-	-

75th Quartile = 41.94 ± 15.83

6- Shell Cowns without Metal Reinforcement

Time Period (months)	Proportion Exposed (Total 167)	Proportion True Failure (Total 31)	Cumulative Proportion Surviving ± SE %
0-6	130.5	0.02	92.2 ± 2.17
6-12	117.5	0.03	89.04 ± 2.60
12-18	106.5	0.02	87.3 ± 2.81
18-24	100.5	0.04	83.9 ± 3.19
24-30	91.0	0.02	82.04 ± 3.38
30-36	80.5	0.02	80.0 ± 3.59
36-42	71.5	0.04	76.6 ± 3.93
42-48	62.0	0.00	76.6 ± 3.93
48-54	51.5	0.02	75.2 ± 4.12
54-60	33.5	0.03	72.9 ± 4.57
60-66	18.0	0.00	72.9 ± 4.57
66-72	9.0	0.00	72.9 ± 4.57
72-78	2.0	0.00	72.9 ± 4.57
78-84	0.5	0.00	72.9 ± 4.57

75th Quartile = 60.43 ± 12.97

7- Shell Crowns with Metal Reinforcement

Time Period (months)	Proportion Exposed (Total 62)	Proportion True Failure (Total 9)	Cumulative Proportion Surviving ± SE %
0-6	38.0	0.03	88.4 ± 4.51
6-12	33.0	0.00	88.4 ± 4.51
12-18	30.0	0.00	88.4 ± 4.51
18-24	27.0	0.00	88.4 ± 4.51
24-30	26.0	0.04	84.9 ± 5.47
30-36	23.0	0.00	84.9 ± 5.47
36-42	20.5	0.00	84.9 ± 5.47
42-48	16.0	0.13	74.3 ± 8.50
48-54	8.0	0.00	74.3 ± 8.50
54-60	5.5	0.00	74.3 ± 8.50
60-66	4.0	0.00	74.3 ± 8.50
66-72	2.0	0.00	74.3 ± 8.50
72-78	0.5	0.00	74.3 ± 8.50
78-84	-	-	-

75th Quartile = 53.62 ± 8.30

8- Total Onlays

Time Period (months)	Proportion Exposed (Total 97)	Proportion True Failure (Total 32)	Cumulative Proportion Surviving ± SE %
0-6	87.5	0.03	90.5 ± 3.01
6-12	84.0	0.05	86.2 ± 3.56
12-18	78.0	0.05	81.8 ± 4.00
18-24	71.5	0.01	80.6 ± 4.11
24-30	67.5	0.06	75.9 ± 4.51
30-36	60.0	0.03	73.3 ± 4.70
36-42	55.5	0.00	73.3 ± 4.70
42-48	48.5	0.04	70.3 ± 4.97
48-54	38.5	0.05	66.7 ± 5.34
54-60	30.5	0.98	60.1 ± 6.01
60-66	21.0	0.00	60.1 ± 6.01
66-72	15.5	0.00	60.1 ± 6.01
72-78	7.5	0.13	52.1 ± 9.10
78-84	0.5	0.00	52.1 ± 9.10

75th Quartile = 38.02 ± 9.48

9- Total Shell Crowns

Time Period (months)	Proportion Exposed (Total 229)	Proportion True Failure (Total 40)	Cumulative Proportion Surviving ± SE %
0-6	168.5	0.02	91.2 ± 1.98
6-12	150.5	0.03	88.8 ± 2.27
12-18	136.5	0.01	87.5 ± 2.42
18-24	127.5	0.03	84.8 ± 2.70
24-30	117.0	0.03	82.6 ± 2.91
30-36	103.5	0.02	80.98 ± 3.06
36-42	92.0	0.03	78.3 ± 3.32
42-48	78.0	0.03	76.3 ± 3.53
48-54	59.5	0.02	75.1 ± 3.69
54-60	39.0	0.03	73.1 ± 4.07
60-66	22.0	0.00	73.1 ± 4.07
66-72	11.0	0.00	73.1 ± 4.07
72-78	2.5	0.00	73.1 ± 4.07
78-84	0.5	0.00	73.1 ± 4.07

75th Quartile = 60.15 ± 13.71

10- Cantilever Bridges

Time Period (months)	Proportion Exposed (Total 49)	Proportion True Failure (Total 7)	Cumulative Proportion Surviving ± SE %
0-6	36.0	0.00	100.0 ± 0.00
6-12	32.0	0.00	93.8 ± 4.28
12-18	28.0	0.06	87.05 ± 6.05
18-24	24.5	0.07	83.5 ± 6.77
24-30	20.5	0.04	79.4 ± 7.56
30-36	18.0	0.05	79.4 ± 7.56
36-42	16.5	0.00	79.4 ± 7.56
42-48	12.5	0.00	79.4 ±7.56
48-54	8.0	0.00	79.4 ± 7.56
54-60	6.0	0.00	79.4 ± 7.56
60-66	4.0	0.00	79.4 ± 7.546
66-72	1.5	0.00	79.4 ± 7.56
72-78	0.5	0.00	79.4 ± 7.56
78-84	-	-	-

75th Quartile = Not Provided

11- Fixed-Fixed Bridges

Time Period (months)	Proportion Exposed (Total 27)	Proportion True Failure (Total 16)	Cumulative Proportion Surviving ± SE %
0-6	24.5	0.08	82.2 ± 7.24
6-12	22.0	0.05	78.4 ± 7.81
12-18	20.5	0.097	70.8 ± 8.72
18-24	17.5	0.11	62.7 ± 9.42
24-30	15.0	0.00	62.7 ± 9.42
30-36	14.5	0.00	62.7 ± 9.42
36-42	14.0	0.14	53.7 ± 9.98
42-48	11.5	0.00	53.7 ± 9.98
48-54	11.0	0.18	43.97 ± 10.28
54-60	6.0	0.00	43.97 ± 10.28
60-66	3.0	0.00	43.97 ± 10.28
66-72	1.5	0.00	43.97 ± 10.28
72-78	-	-	-
78-84	-	-	-

75th Quartile = 20.69 ± 6.65

12- Mirage Luting Cement

Time Period (months)	Proportion Exposed (Total 102)	Proportion True Failure (Total 31)	Cumulative Proportion Surviving ± SE %
0-6	86.5	0.02	90.8 ± 2.93
6-12	80.5	0.06	85.1 ± 3.68
12-18	73.0	0.03	82.8 ± 3.93
18-24	69.0	0.06	78.01 ± 4.37
24-30	63.0	0.05	74.3 ± 4.66
30-36	57.0	0.035	71.7 ± 4.85
36-42	50.0	0.04	68.9 ± 5.06
42-48	39.0	0.03	67.1 ± 5.23
48-54	27.0	0.07	62.1 ± 5.90
54-60	19.0	0.05	58.8 ± 6.44
60-66	15.0	0.00	58.8 ± 6.44
66-72	8.5	0.00	58.8 ± 6.44
72-78	3.0	0.00	58.8 ± 6.44
78-84	1.0	0.00	58.8 ± 6.44

75th Quartile = 34.86 ± 8.20

13- Ultra-Bond Luting Cement

Time Period (months)	Proportion Exposed (Total 252)	Proportion True Failure (Total 47)	Cumulative Proportion Surviving ± SE %
0-6	218.5	0.03	92.04 ± 1.75
6-12	205.0	0.01	90.7 ± 1.89
12-18	198.5	0.03	87.95 ± 2.14
18-24	186.5	0.01	87.0 ± 2.22
24-30	177.5	0.02	85.04 ± 2.38
30-36	164.0	0.02	83.5 ± 2.50
36-42	154.0	0.01	82.4 ± 2.58
42-48	142.0	0.02	80.7 ± 2.71
48-54	124.0	0.01	80.01 ± 2.77
54-60	98.0	0.03	77.6 ± 3.02
60-66	60.5	0.00	77.6 ± 3.02
66-72	35.0	0.00	77.6 ± 3.02
72-78	13.0	0.08	71.6 ± 6.38
78-84	-	-	-

75th Quartile = 80.58 ± -

14- Insure Luting Cement

Time Period (months)	Proportion Exposed (Total 62)	Proportion True Failure (Total 2)	Cumulative Proportion Surviving ± SE %
0-6	30.0	0.03	94.7 ± 3.78
6-12	21.5	0.00	94.7 ± 3.78
12-18	13.0	0.00	94.7 ± 3.78
18-24	8.0	0.00	94.7 ± 3.78
24-30	6.5	0.00	94.7 ± 3.78
30-36	6.0	0.00	94.7 ± 3.78
36-42	5.5	0.00	94.7 ± 3.78
42-48	2.5	0.00	94.7 ± 3.78
48-54	-	-	-
54-60	-	-	-
60-66	-	-	-
66-72	-	-	-
72-78	-	-	-
78-84	-	-	-

75th Quartile = Not Provided

15- Bruxer Patients

Time Period (months)	Proportion Exposed (Total 54)	Proportion True Failure (Total 15)	Cumulative Proportion Surviving ± SE %
0-6	47.5	0.00	96.2 ± 2.62
6-12	45.0	0.04	91.95 ± 3.87
12-18	42.5	0.094	83.3 ± 5.41
18-24	36.5	0.03	81.01 ± 5.72
24-30	30.5	0.00	81.01 ± 5.72
30-36	25.5	0.04	77.8 ± 6.32
36-42	22.5	0.00	77.8 ± 6.32
42-48	22.0	0.00	77.8 ± 6.32
48-54	20.5	0.05	74.04 ± 7.06
54-60	14.5	0.27	53.6 ± 10.08
60-66	7.0	0.00	53.6 ± 10.08
66-72	3.5	0.00	53.6 ± 10.08
72-78	-	-	-
78-84	-	-	-

75th Quartile = 58.48 ± 5.21

16- Non-Bruxer Patients

Time Period (months)	Proportion Exposed (Total 460)	Proportion True Failure (Total 86)	Cumulative Proportion Surviving ± SE %
0-6	361.0	0.03	91.7 ± 1.37
6-12	325.5	0.03	89.2 ± 1.57
12-18	298.5	0.03	86.8 ± 1.74
18-24	275.0	0.03	84.2 ± 1.90
24-30	256.5	0.03	81.6 ± 2.06
30-36	237.5	0.02	80.3 ± 2.14
36-42	220.0	0.03	87.1 ± 2.26
42-48	187.0	0.02	76.4 ± 2.36
48-54	150.5	0.03	74.3 ± 2.50
54-60	115.5	0.00	74.4 ± 2.50
60-66	76.5	0.00	74.4 ± 2.50
66-72	44.0	0.00	74.4 ± 4.85
72-78	17.0	0.06	69.9 ± 4.85
78-84	1.0	0.00	69.9 ± 4.85

75th Quartile = 58.14 ± 8.96

17- Age Group (10-20)

Time Period (months)	Proportion Exposed (Total 61)	Proportion True Failure (Total 6)	Cumulative Proportion Surviving ± SE %
0-6	46.0	0.00	98.2 ± 1.77
6-12	40.0	0.03	95.8 ± 2.98
12-18	37.0	0.03	93.2 ± 3.86
18-24	34.0	0.03	90.4 ± 4.62
24-30	30.5	0.00	90.4 ± 4.62
30-36	29.0	0.00	90.4 ± 4.62
36-42	26.5	0.08	83.6 ± 6.31
42-48	20.5	0.00	83.6 ± 6.31
48-54	18.0	0.00	83.1 ± 6.31
54-60	11.0	0.00	83.6 ± 6.31
60-66	2.0	0.00	83.6 ± 6.31
66-72	-	-	-
72-78	-	-	-
78-84	-	-	-

75th Quartile = Not Provided

18- Age Group (21-30)

Time Period (months)	Proportion Exposed (Total 90)	Proportion True Failure (Total 8)	Cumulative Proportion Surviving ± SE %
0-6	61.5	0.02	97.1 ± 2.01
6-12	51.5	0.00	97.1 ± 2.01
12-18	46.0	0.02	95.02 ± 2.87
18-24	42.0	0.00	95.02 ± 2.87
24-30	41.0	0.00	95.02 ± 2.87
30-36	38.0	0.05	90.02 ± 4.39
36-42	33.5	0.06	84.7 ± 5.53
42-48	27.0	0.00	84.7 ± 5.53
48-54	21.5	0.05	80.7 ± 6.53
54-60	15.5	0.00	80.7 ± 6.53
60-66	7.5	0.00	80.7 ± 6.53
66-72	2.0	0.00	80.7 ± 6.53
72-78	1.0	0.00	80.7 ± 6.53
78-84	0.5	0.00	80.7 ± 6.53

75th Quartile = Not Provided

19- Age Group (31-40)

Time Period (months)	Proportion Exposed (Total 105)	Proportion True Failure (Total 33)	Cumulative Proportion Surviving ± SE %
0-6	91.0	0.07	87.9 ± 3.28
6-12	82.5	0.02	85.8 ± 3.53
12-18	79.0	0.08	79.3 ± 4.14
18-24	70.5	0.04	75.9 ± 4.40
24-30	62.5	0.03	73.5 ± 4.58
30-36	56.0	0.04	70.8 ± 4.78
36-42	51.0	0.00	70.8 ± 7.78
42-48	45.5	0.07	66.1 ± 5.17
48-54	34.5	0.06	62.3 ± 5.54
54-60	25.5	0.00	62.3 ± 5.54
60-66	21.5	0.00	62.3 ± 5.54
66-72	14.0	0.00	62.3 ± 5.54
72-78	4.5	0.22	48.5 ± 12.95
78-84	-	-	-

75th Quartile = 32.21 ± 10.50

20- Age Group (41-50)

Time Period (months)	Proportion Exposed (Total 154)	Proportion True Failure (Total 26)	Cumulative Proportion Surviving ± SE %
0-6	118.0	0.00	95.04 ± 1.83
6-12	111.5	0.04	90.8 ± 1.83
12-18	99.0	0.02	88.9 ± 2.55
18-24	93.0	0.03	86.1 ± 2.81
24-30	88.0	0.06	81.2 ± 3.17
30-36	76.0	0.00	81.2 ± 3.67
36-42	69.5	0.01	80.01 ± 3.67
42-48	57.5	0.02	78.6 ± 3.80
48-54	45.5	0.02	76.9 ± 3.98
54-60	39.0	0.03	74.9 ± 4.25
60-66	25.0	0.00	74.9 ± 4.58
66-72	11.0	0.00	74.9 ± 4.58
72-78	3.0	0.00	74.9 ± 4.58
78-84	-	-	74.9 ± 4.58

75th Quartile = 65.76 ± 25.71

21- Age Group (51+)

Time Period (months)	Proportion Exposed (Total 104)	Proportion True Failure (Total 28)	Cumulative Proportion Surviving ± SE %
0-6	92.0	0.09	86.3 ± 3.40
6-12	85.0	0.05	86.3 ± 3.71
12-18	80.0	0.04	81.2 ± 3.90
18-24	72.0	0.03	78.9 ± 4.10
24-30	65.0	0.03	77.7 ± 4.22
30-36	64.0	0.02	76.5 ± 4.32
36-42	62.0	0.02	75.3 ± 4.42
42-48	58.5	0.00	75.3 ± 4.42
48-54	51.5	0.02	73.8 ± 4.57
54-60	39.0	0.08	68.1 ± 5.27
60-66	27.5	0.00	68.1 ± 5.27
66-72	20.5	0.00	68.1 ± 5.27
72-78	8.5	0.00	68.1 ± 5.27
78-84	0.5	0.00	68.1 ± 5.27

75th Quartile = 55.06 ± 22.01

22- Gender (Male)

Time Period (months)	Proportion Exposed (Total 197)	Proportion True Failure (Total 35)	Cumulative Proportion Surviving ± SE %
0-6	170.5	0.006	95.2 ± 1.56
6-12	163.0	0.03	92.3 ± 1.98
12-18	152.5	0.05	88.1 ± 2.45
18-24	140.0	0.01	86.8 ± 2.58
24-30	133.0	0.02	85.5 ± 2.70
30-36	125.5	0.02	83.5 ± 2.88
36-42	117.0	0.02	82.03 ± 3.00
42-48	100.0	0.00	82.03 ± 3.00
48-54	82.5	0.02	80.04 ± 3.24
54-60	63.5	0.05	76.3 ± 3.75
60-66	38.0	0.00	76.3 ± 3.75
66-72	16.5	0.00	76.3 ± 3.75
72-78	3.0	0.00	76.3 ± 3.75
78-84	0.5	0.00	76.3 ± 3.75

75th Quartile = Not Provided

23- Gender (Female)

Time Period (months)	Proportion Exposed (Total 317)	Proportion True Failure (Total 66)	Cumulative Proportion Surviving ± SE %
0-6	238.0	0.05	90.1 ± 1.81
6-12	207.5	0.03	87.6 ± 2.04
12-18	188.5	0.03	85.2 ± 2.24
18-24	171.5	0.04	81.7 ± 2.50
24-30	154.0	0.04	78.6 ± 2.72
30-36	137.5	0.01	77.4 ± 2.80
36-42	125.5	0.03	74.6 ± 2.97
42-48	109.0	0.04	72.2 ± 3.16
48-54	88.5	0.03	69.8 ± 3.36
54-60	66.5	0.02	68.7 ± 3.47
60-66	45.5	0.00	68.7 ± 3.47
66-72	31.0	0.00	68.7 ± 3.47
72-78	14.0	0.07	63.8 ± 5.72
78-84	0.5	0.00	63.8 ± 5.72

75th Quartile = 47.88 ± 6.84

24- Arch Distribution (Posterior Maxilla)

Time Period (months)	Proportion Exposed (Total 81)	Proportion True Failure (Total 22)	Cumulative Proportion Surviving ± SE %
0-6	77.0	-	93.8±2.70
6-12	75.0	-	91.4 ± 3.10
12-18	68.0	-	87.5 ± 3.70
18-24	64.0	-	84.8 ± 4.10
24-30	60.0	-	84.8 ± -
30-36	55.0	-	80.5 ± -
36-42	50.0	-	80.5 ± -
42-48	45.0	-	80.5 ± -
48-54	28.0	-	76.1 ± -
54-60	24.0	-	72.9 ± 5.90
60-66	19.0	-	58.5 ± 8.0
66-72	13.0	-	58.5 ± -
72-78	8.0	-	58.5 ± -
78-84	3.0	-	58.5 ± -

75th Quartile = 57.00 ± -

25- Arch Distribution (Posterior Mandible)

Time Period (months)	Proportion Exposed (Total 107)	Proportion True Failure (Total 36)	Cumulative Proportion Surviving ± SE %
0-6	86.0	-	89.2 ± 3.08
6-12	77.0	-	84.9 ± 3.06
12-18	73.0	-	80.4 ± 4.05
18-24	63.0	-	76.8 ± 4.38
24-30	59.0	-	71.8 ± 4.74
30-36	52.0	-	66.7 ± 5.06
36-42	42.0	-	62.0 ± 5.37
42-48	37.0	-	60.5 ±-
48-54	32.0	-	60.5 ± -
54-60	25.0	-	58.2 ± -
60-66	25.0	-	58.2 ± -
66-72	17.0	-	58.2 ± -
72-78	9.0	-	58.2 ± -
78-84	6.0	-	50.9 ± -

75th Quartile = 28.00 ± -

26- Operator 1

Time Period (months)	Proportion Exposed (Total 301)	Proportion True Failure (Total 53)	Cumulative Proportion Surviving ± SE %
0-6	262.0	0.03	92.3 ± 1.58
6-12	246.5	0.01	91.2 ± 1.69
12-18	239.0	0.03	88.5 ± 1.92
18-24	224.0	0.01	87.3 ± 2.01
24-30	210.5	0.01	86.1 ± 2.11
30-36	195.5	0.02	84.8 ± 2.21
36-42	184.5	0.01	83.8 ± 2.28
42-48	169.5	0.02	81.9 ± 2.43
48-54	147.0	0.01	80.7 ± 2.52
54-60	118.0	0.03	78.7 ± 2.72
60-66	76.5	0.00	78.7 ± 2.72
66-72	44.0	0.00	78.7 ± 2.72
72-78	16.5	0.06	73.9 ± 5.28
78-84	1.0	0.00	73.9 ± 5.28

75th Quartile = 82.63 ± 7.31

27- Operator 2

Time Period (months)	Proportion Exposed (Total 213)	Proportion True Failure (Total 48)	Cumulative Proportion Surviving ± SE %
0-6	146.5	0.03	92.2 ± 2.03
6-12	124.0	0.06	86.2 ± 2.78
12-18	102.0	0.05	81.9 ± 3.22
18-24	87.5	0.07	76.4 ± 3.73
24-30	76.5	0.07	71.4 ± 4.10
30-36	67.5	0.03	69.3 ± 4.24
36-42	58.0	0.07	64.5 ± 4.57
42-48	39.5	0.00	64.5 ± 4.57
48-54	24.0	0.13	56.4 ± 5.91
54-60	12.0	0.08	51.7 ± 7.05
60-66	7.0	0.00	51.7 ± 7.05
66-72	3.5	0.00	51.7 ± 7.05
72-78	0.5	0.00	51.7 ± 7.05
78-84	-	-	-

75th Quartile = 31.63 ± 4.48

Appendix VI

Form 1 : duplicate assessments from 30 dies

1. General features of the EPRB preparations

Feature	Site - Kappa Values[1]	
	Mesial	Distal
Gingival margins in dentine/cementation	1.00	1.00
Fissures left at cavo surface margins	0.53	0.63
Margins bevelled occlusally and gingivally	0.89	1.00
Preparation taper <20^0	1.00	0.61

2. Measurements of the EPRB preparations

Measurement (mm)	Site - P values (paired t-tests)[2]	
	Mesial	Distal
Intercuspal width	0.35	0.79
Isthmus width	0.14	0.27
Proximal width	0.17	0.09
Height of axial wall	0.35	1.00
Depth of occlusal floor	0.43	0.38
Cusp reduction (buccal)	0.78	0.19
Cusp reduction (lingual)	0.15	0.79

1. Kappa values show good to excellent agreements for examiner reliability.

2. Paired t-tests show no significant differences between any of the original and duplicate measurements.

Form 2 : duplicate assessments from 30 restorations

Feature	% age agreement	Kappa Values
Failure type :		
Sensitive pulpitis	100	
Secondary caries	100	
Food impaction	100	
Colour mismatch	100	
Debonding	100	
Bulk fracture	100	1.00
Chip fracture	100	
Connector fracture	100	
Microfracture	100	
Failure reason :		
Microleakage	100	1.00
Poor anat./preparation	100	
Poor etch/contamin	100	
Poor enamel quality	100	
Poor enamel quantity	100	
Occlusal stress	100	
Tooth mobile	100	
Restoration not seated	100	
Poor colour match	100	
Trauma	100	
Treatment given :		
None/adjust	100	
Resin repair	100	1.00
Remake	100	
Replace by different material	100	
Rebond	100	
Root canal filling	100	1.00
Other treatment	100	