Fracture resistance of molars restored with different types of ceramic partial coverage restorations.

An in-vitro study
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1. Introduction

Dental caries is one of the most common diseases, affecting approximately 80% of the population in developed countries (Agerholm & Sidi 1988, Burke et al. 1999). Finding a material that could restore the lost tooth structure and combine physical, chemical and aesthetic properties which are optimal has been the goal of research for many years. The science of dental materials is considered one of the most important issues in contemporary dentistry, and has led to the development of many alternatives for restoring lost tooth structure particularly in the posterior region.

Amalgam is one of the most frequently used materials in dentistry, with an annual failure rate between 0% to 7% over an observation period of up to 20 years (Hickel & Manhart 2001). Despite the controversy about its safety and efficacy (al-Nazhan et al. 1988, Lindberg et al. 1994), amalgam has been around for more than 100 years. Among its advantages are the relative low cost, ease of handling and placement and the longevity of the restoration (Roulet 1997b, Chen et al. 2000, Grobler et al. 2000). Although recent studies have proven that the use of dental amalgam has little or no adverse effects (Ganss et al. 2000), an intensive public debate about the alleged adverse effects of dental amalgam led to a significant limitation of its use and to patients feeling a deep sense of insecurity (Eley 1997a, b, c).

Since the beginning of the twentieth century cast gold restorations have made up a significant portion of all posterior tooth restorations. This is due to the superior physical and chemical properties of the material. When dentists are asked about their favorite restoration for their own teeth, gold cast restorations are most often the preferred choice (Christensen 1989). Studies of the longevity of cast gold restorations have produced conflicting results (Kerschbaum & Voss 1981, Presern & Strub 1983, Jahn & Gonschorek 1986, Frtiz et al. 1992, Studer et al. 2000). However, recently published data show that cast gold restorations have an annual failure rate of only 0% to 5.9% with observation periods of up to 15 years (Hickel & Manhart 2001). With such results cast gold remains a standard restorative material for posterior teeth (Christensen 1989, 1996a, Eley 1997c, Stoll et al. 1999, Studer et al. 2000, Hickel & Manhart 2001).
Increasing demands for alternative restorative materials that are aesthetically pleasing has led to the development of tooth-coloured restorative materials. Materials available until 1978 were very inadequate and had short clinical longevity. Since 1978, various materials have shown the ability to serve more than 10 years (Christensen 1989). Glass-ionomer cements are not considered to possess adequate mechanical properties for general use as definitive restorations in stress-bearing posterior teeth (Caughman et al. 1990, Eley 1997c, van Dijken & Sjostrom 1998, Hickel & Manhart 2001). Recently developed resin composites are superior to the earlier versions in regard to wear, resistance and colour stability, but the predominant shortcoming of the composites is the polymerisation shrinkage (Davidson et al. 1984, Feilzer et al. 1987, Ciucchi et al. 1997). During recent years several techniques have been introduced to solve existing problems with resin composites, such as multiple increment techniques, replacement of the dentin with glass ionomer cement in the sandwich technique, or the use of ceramic inserts (Krejci et al. 1987, van Dijken et al. 1999). However, these techniques still suffer from imperfections and are very technique sensitive (Roulet 1997a, van Dijken 2000). A promising method, the inlay/onlay technique, has also been introduced to reduce the shrinkage problem (Mörmann 1982, James & Yarovesky 1983, Blankenau et al. 1984). The form of the restoration can be established by a direct, indirect or semidirect method. Unfortunately, with only one exception (Roulet 1994), no clinical studies fulfilled the criteria of a long-term study (5 years) on the success rate of this technique (James & Yarovesky 1983, Füllemann et al. 1992, Krejci 1992). Furthermore, clinical studies have demonstrated a failure of the composite-composite bond (60% marginal openings after 6 months) (Krejci 1992, Roulet 1997a).

Along with metals and polymers, ceramics are one of the basic groups of materials. For decades they have been recognized as one of the earliest and most environmentally-durable materials known to man. Developing dental ceramics is one of the most important subjects in the field of dental materials. In the last few years, several new all-ceramic systems, which offered good aesthetics and simplified fabrication procedures, have been introduced. With these systems it is possible to fabricate single crowns, inlays, onlays and veneers. These all-ceramic restorations represent an interesting option to aesthetic restorative
treatment of lost tooth structure and can be made by using a variety of fabrication techniques.

However, in vitro and in vivo investigations of new all-ceramic systems should be undertaken before introducing them into routine clinical use.
2. Literature review

2.1 History of porcelain and its use in dentistry

The word ceramic is derived from the Greek word “Keramos”, meaning of or pertaining to pottery, especially as an art form. Porcelain is defined as a fine kind of earthenware, having a translucent body and a transparent glaze, or as an article or vessel made of porcelain (Qualtrough et al. 1990). Ceramics were probably the first materials to be artificially made by humans, and porcelain was among the first materials to be the subject of early laboratory research by scientists. Primitive man would have become aware of the plastic properties of mud and clay and might have accidentally discovered that molded shapes baked in fire became hard. Examples of the early fabrication of ceramic articles have been found and dated as far back as 23,000 years BC. However, the earliest examples of porcelain known, date back a thousand years to the Sung dynasty (960 to 125 AD) (Jones 1985).

Although dental technology existed in Etruria as early as 700 BC and during the Roman first century (Kelly et al. 1996), the history of porcelain as a dental material only goes back approximately 200 years (Jones 1985). It was found that, by using this material, it was possible to reproduce the color and translucency of natural teeth, and the first porcelain teeth were thus manufactured (Qualtrough et al. 1990).

In 1774, Alexis Duchateau and Nicholas Dudois de Chemant fabricated the first successful porcelain dentures. Dubois de Chemant, who improved porcelain formulations continually, was awarded both French and British patents. In 1808, individually-formed porcelain teeth which contained embedded platinum foils were introduced in Paris by Giuseppangelo Fonzi. Their aesthetic and mechanical versatility provided a major advance in prosthetic dentistry (Kelly et al. 1996, Pröbster 1997). Single-tooth porcelain restorations were first introduced in 1844. The porcelain jacket crown is said to have originated from the gold shell crown, the idea which was credited to Beers of California in 1873. The porcelain crown was constructed on the same principle and basic theory, but was capable of better esthetic results regarding shades and translucency. The preparation and fabrication
procedures for porcelain crowns were more complex in comparison to inlays; for this reason, the major use of dental porcelain between 1900 and 1920 was for inlay work (Jones 1985).

The technique for making individual porcelain inlays and crowns was not developed until the late 1800s. An early technique, described by Herbst in 1882, was one in which porcelain rods were ground, fitted and cemented into prepared cavities in the natural tooth (Jones 1985, Touati 1996). The first successful fused inlays and crowns were said to be made by Land of Detroit, in about 1886. A patent was taken out by Land in 1887 covering the method of a burnishing platinum foil in order to make a matrix for fusing the porcelain with the aid of a gas furnace. Land also experimented with producing a low-fusing porcelain that would be compatible with a gold matrix. However, he had little success with the low-fusing porcelain (Jones 1985, Qualtrough et al. 1990).

During the late 1950s and 1960s there were marked advances in the development of new techniques, materials, and equipment, such as furnaces, alloys and porcelain frits. Improved tooth-cavity preparation, using techniques based upon new, high-speed instrumentation and burs combined with the introduction of improved and more accurate impression techniques, vastly changed clinical approaches and attitudes regarding porcelain restorations (Qualtrough et al. 1990, Pröbster 1997). One of the most significant advances occurred with the successful introduction of the acid-etch technique by Buonocore (1955), which opened a new era for adhesive dentistry and development of new dental materials (Qualtrough et al. 1990).

2.2 Definition of Inlay/ onlay restorations

According to the Glossary of Prosthodontic terms (The Academy of Prosthodontics 1999), an inlay is a dental restoration made outside of a tooth to correspond to the form of the prepared cavity, which is then luted into the tooth. An onlay is a restoration that restores the entire occlusal surface and is retained by mechanical or adhesive means.
2.3 Development of ceramic inlay and onlay restorations

Formulating an ideal strength-aesthetic combination in a ceramic material has been a battle for many years. Traditional porcelain is a blend of three minerals: quartz, feldspar and pure white clay ($\text{Al}_2\text{O}_3.2\text{SiO}_2.x\text{H}_2\text{O}$). Pigments and opacifying agents are added to this type of porcelain in order to produce various shades and translucencies. After baking, the porcelain contains similar components: small crystals (leucite) and/or alumino-silicate crystals embedded in a silicate glass (a non-crystalline, amorphous matrix). Leucite, a reaction product of potassium feldspar and glass, is responsible for optical properties, thermal expansion, strength, and hardness of the porcelain (Rosenblum & Schulman 1997).

In the early 1980s, castable glass-ceramic and refractory die techniques were introduced. The disadvantages of the refractory die system are that the particles are sintered together, resulting in microporosities and inhomogeneities between the ceramic particles. It is well known that these microporosities can initiate crack propagation, leading to early failure of such all-ceramic restorations (Kelly et al. 1996). Many castable glass-ceramic systems have been described in which the porosities could be reduced to a minimum by the casting technique (Dicor, Dentsply, York, Pennsylvania, USA/ Cerapearl, Kyocera Bioceramics, Kyoto, Japan/). However, the casting process is followed by a ceramming procedure (controlled crystallization using an appropriate heat treatment), resulting in additional ceramic shrinkage (Kelly et al. 1996).

In 1990, the IPS Empress all-ceramic system was developed (Beham 1990). It is a leucite-reinforced glass-ceramic material, which can be deformed at elevated temperatures and can be pressed into a mould. This method provides a high degree of homogeneity, high precision and good aesthetic appearance (Beham 1990, 1991, Dong et al. 1992). With a flexural strength of 200 MPa, the system is considered one of the most preferred restorative options for the fabrication of single crowns, inlays/onlays, and veneers. (Dong et al. 1992, Kelly et al. 1996).
2.4 Classification of contemporary all-ceramic systems used for the fabrication of inlays and onlays

Contemporary all-ceramic systems can be classified either by material composition or by fabrication procedures (Kelly et al. 1996, Rosenblum & Schulman 1997, van Dijken 1999).

2.4.1 Sintered ceramics (powder slurry ceramics)

Stronger all-ceramic systems were developed by increasing the crystalline content of conventional feldspathic porcelain. All systems used the refractory die technique.

- **Optec HSP** (Jeneric/Pentron, Wellingford, USA, Connecticut)

  The material is a feldspathic porcelain containing 40% leucite crystals. With the increased amount of leucite, the material has a flexural strength of 146 MPa (Rosenblum & Schulman 1997). The manufacturer disperses the leucite crystals in a glassy matrix by controlling their nucleation and crystal growth during the initial production of the porcelain powder. In the so-called refractory die technique, the porcelain is built up on a model in layers, using a powder-water slurry. The layering technique produces a less controlled crystallization (van Dijken 1999). Optec ceramic is indicated for inlays, onlays, and veneers (Garber & Goldstein 1994). The marginal integrity of Optec inlays was rated excellent for 67% in a clinical follow-up study of 8.1 months (Molin & Karlsson 1992). The failure rate of 145 Optec inlays was 13% after 3 years of function (Molin & Karlsson 1996). The main reason for failure was fracture of the inlays. Due to the high leucite content, the material’s abrasiveness against a natural tooth is greater than that of conventional feldspathic porcelain (Rosenblum & Schulman 1997).

- **Duceram LFC** (Ducera Dental, D-Rosbach)

  The material is a hydrothermal low-fusing ceramic material with a flexural strength of 110 MPa. It is composed of an amorphous glass containing hydroxyl ions. The
material’s hardness is close to the hardness of natural teeth owing to the absence of leucite (Rosenblum & Schulman 1997). The application of the material is limited to inlays, onlays, veneers and crowns. The restoration is made in two layers; the base layer is Duceram Metal Ceramic (a leucite containing porcelain), which is placed on a refractory die using standard powder-slurry technique; the veneering layer is Duceram LFC (Rosenblum & Schulman 1997). It has been reported that Duceram inlays have a marginal gap of 72 µm (Gemalmaz et al. 1997). The survival rate of 53 inlays was 90% after three years of function (Haas et al. 1992).

- **Hi Ceram** (Vita Zahnfabrik, D-Bad Säckingen)

Hi-Ceram is an alumina-based ceramic material. It is indicated for the fabrication of inlays, onlays and veneers. Fabrication procedures of restorations using this material are the same procedures when using other sintered ceramic systems. In a longitudinal study, 30 inlays showed a survival rate of 80% over an observation period of 3 years. The main reasons for failure were either fracture of the inlays or secondary caries (Haas et al. 1992).

- **Mirage / Mirage II** (Chameleon Dental Products, USA, Kansas city)

Mirage and Mirage II are feldspathic ceramic materials reinforced with zirconia fibers. The size of the fibers differentiate the two materials. In a clinical study, 25 inlays showed a survival rate of 52% after 4.5 years of function (Isidor & Brondum 1995). The main reasons for failure were fractures of the inlays. In a three-year comparative study, 118 inlays (59 each group) were either luted with glass-ionomer cement or composite resin cement and examined intraindividually. They showed survival rates of 84.7% and 96.6%, respectively (Aberg et al. 1994). In another 6-year comparative study, the survival rate was 74% for 59 inlays luted with glass-ionomer cement and 88% for 59 inlays luted with composite resin cement (van Dijken et al. 1998). It was concluded from this study that higher failure rates could be expected in restorations luted with glass-ionomer cement.
Fifty inlays fabricated with Mirage II showed a survival rate of 100% after an observation period of 4 years. 64% of the margins were clinically perceptible after 4 years (Friedl et al. 1997).

The disadvantage of all-ceramic restorations, made with sintering techniques, is that sintering the particles together can result in microporosities and inhomogeneties between the particles, which can initiate crack formation (van Dijken 1999).

### 2.4.2 Pressable ceramics

- **IPS Empress I** (Ivoclar-Vivadent, FL-Schaan)

To overcome the processing of inhomogeneities and porosity during ceramming, a heat-press technique (IPS-Empress) was developed in 1983 by faculty members of the Department of Fixed and Removable Prosthodontics and Dental Materials at the University of Zurich. Since 1986 the development has proceeded in conjunction with a dental company (Ivoclar-Vivadent, FL-Schaan).

The IPS Empress I material is a type of leucite-reinforced glass-ceramic material supplied in ingot form. The glass-ceramic ingot is precerammed and precolored (Dong et al. 1992). This material is derived from the SiO$_2$-Al$_2$O$_3$-K$_2$O chemical system. Leucite crystals represent framework silicates with the chemical formula KalSi$_2$O$_6$. Depending on the type of the IPS Empress I product, the content of the crystal phase ranges between 30 and 40 vol%. The material has a flexural strength of 182 MPa following heat treatment. Therefore, the IPS Empress I system is designed for the fabrication of single units, inlays, onlays and veneers (Dong et al. 1992). The strengthening mechanism of leucite is attributed to the higher percentage volume reduction of leucite particles compared to the surrounding glass matrix upon cooling (Seghi et al. 1995). The higher percentage volume reduction of leucite is accounted for by its higher coefficient of thermal expansion in comparison to the glass matrix and a high-to-low temperature phase transformation. The volume differential between the leucite particles and the glass matrix causes residual stresses that place the surrounding glass matrix in compression, which must be counteracted by tensile stresses before cracks propagate (Dong et al. 1992, Seghi...
et al. 1995). It has also been shown that flexural strength improves under subsequent heat treatments as a result of the growth of additional leucite crystals (Dong et al. 1992).

A full-contour restoration is waxed-up on a conventional die system. The wax-up is then sprued, invested and placed in a special mold that has an alumina plunger. The ring is placed in a cold burn-out oven and progressively heated to 850 °C and held at this temperature for 90 minutes for wax burnout and heat saturation. The ring is then ready for placement in the EP 500 (Ivoclar-Vivadent, FL-Schaan) pressing furnace, which is in a standby mode at a temperature of 700 °C. One or two precerammed ingots of the desired color are placed in the center of the sprue former. Once the process is initiated, the entire assembly is heated to 1150 °C under a vacuum and the plunger presses the molten ceramic into the mold. Afterwards, the final shade of the restoration is adjusted by staining or veneering. In the veneering technique, the original wax-up is cut back by about 0.3 mm. After molding and baking as described, feldspathic porcelain is added to the surface to obtain full contour and the correct shade.

Short- and long-term clinical studies on Empress I inlays and onlays showed very good survival rates (Table 2.1).

<table>
<thead>
<tr>
<th>Author (year)</th>
<th>Observation period</th>
<th>Type (No.)</th>
<th>Survival rate</th>
<th>Complications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Krejci et al. (1992)</td>
<td>1.5 years</td>
<td>Inlays class II (10)</td>
<td>100%</td>
<td>Inlay fracture</td>
</tr>
<tr>
<td>Tidehag &amp; Gunne (1995)</td>
<td>2 years</td>
<td>Inlays &amp; onlays (62)</td>
<td>98.4%</td>
<td>1 onlay fractured</td>
</tr>
<tr>
<td>Studer et al. (1996)</td>
<td>2 years</td>
<td>Inlays &amp; onlays (130)</td>
<td>97.5%</td>
<td>Inlay fracture</td>
</tr>
<tr>
<td>Thonemann et al. (1997)</td>
<td>2 years</td>
<td>Inlays (51)</td>
<td>100%</td>
<td>Significant deterioration of marginal quality over time</td>
</tr>
<tr>
<td>Fradeani et al. (1997)</td>
<td>4.5 years</td>
<td>Inlays &amp; onlays (125)</td>
<td>95.6%</td>
<td>Restoration fracture</td>
</tr>
<tr>
<td>Lehner et al. (1998)</td>
<td>6 years</td>
<td>Inlays (138)</td>
<td>94.9%*</td>
<td>7 onlays fractured</td>
</tr>
<tr>
<td>Scheibenbogen et al. (1998)</td>
<td>1 year</td>
<td>Inlays class I (24)</td>
<td>100%</td>
<td>-</td>
</tr>
<tr>
<td>Study</td>
<td>Duration</td>
<td>Type &amp; Description</td>
<td>Survival Rate</td>
<td>Failure Mode</td>
</tr>
<tr>
<td>------------------------------</td>
<td>----------</td>
<td>--------------------</td>
<td>---------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>Krämer et al. (1999)</td>
<td>4 years</td>
<td>Inlays (96)</td>
<td>93%</td>
<td>Inlay fracture caries</td>
</tr>
<tr>
<td>Frankenberger et al. (2000)</td>
<td>6 years</td>
<td>Inlays (96)</td>
<td>93%*</td>
<td>7 inlays failed</td>
</tr>
<tr>
<td>Manhart et al. (2001)</td>
<td>3 years</td>
<td>Inlays class I &amp; II (24)</td>
<td>100%</td>
<td>-</td>
</tr>
<tr>
<td>van Dijken et al. (2001)</td>
<td>5 years</td>
<td>Total coverage restorations without macromechanical retention (182)</td>
<td>92% with chemical cured resin composite</td>
<td>95% with dual-cured resin composite</td>
</tr>
</tbody>
</table>

* Estimated survival (Kaplan-Meier analysis)

Table 2.1 Survival rates of Empress I inlays and onlays

- **Optec OPC** (Jeneric/Pentron, Wellingford, USA, Connecticut)

This material is a type of feldspathic porcelain with increased leucite content, processed by molding under pressure and heat. The OPC system can be used for full-contour restorations (inlays, onlays, veneers, full crowns). Alternatively, it can be used as a core material, which is veneered using conventional powder-slurry techniques with a high-leucite-content feldspathic porcelain, similar to Optec HSP porcelain. The manufacturer reports that the crystalline leucite particle size has been reduced and the leucite content increased, resulting in an overall increase in flexural strength of OPC (165 MPa) (Kappert 1993, Rosenblum & Schulman 1997).

There are no published clinical studies on Optec OPC (van Dijken 1999). However, because of its high leucite content, it can be expected that this porcelain's abrasion against natural teeth will be greater than that of conventional feldspathic porcelain (Rosenblum & Schulman 1997).
2.4.3 Infiltrated ceramics

- **In-Ceram** (Vita Zahnfabrik, D-Bad Säckingen)

The restoration is composed of an infiltrated core veneered with feldspathic porcelain. The core is extremely porous, and is composed of either alumina oxide or spinel, a composition containing aluminum oxide and magnesium oxide. The core is made from fine insoluble particles that are mixed with water to form a suspension referred to as slip and then painted on a gypsum die. Water, flowing under capillary pressure into the gypsum die, compacts the particles against the die. The procedure is called slip-casting. Afterwards, the compacted particles are partially sintered together to form necks between touching particles for 10 hours at 1120°C. The result is an opaque, porous core. The spinel core is more than twice as translucent as the alumina coping and is more suited for esthetically critical areas and inlays (Kelly et al. 1996, van Dijken 1999). After choosing an appropriate shade, the porous, partially sintered alumina (or spinel) core, is then infiltrated with a low-viscosity glass (Lanthanum glass) by baking again at 1120°C for 4 hours to yield a ceramic coping of high density and strength. The coping contains at least 70% aluminum oxide or spinel and is currently one of the strongest ceramics available with a flexural strength between 236 and 446 MPa depending on the test method used (Seghi & Sorensen 1995, Giordano et al. 1995b). The densely stacked particles and the different thermal expansion coefficients of glass and alumina (or spinel) contribute to the high strength of the material. The In-Ceram material is then veneered with a feldspathic ceramic for the final aesthetics. The core of aluminum oxide or spinel is so dense that conventional etching with hydrofluoric acid is not possible and does not increase the surface roughness and bond of the restoration to the tooth. Adhesive luting is possible after sandblasting and the use of a resin cement containing a phosphate monomer, i.e., Panavia 21 (Kern & Thompson 1995, Kern & Strub 1998). The material has a hardness equal to that of conventional feldspathic porcelain (Rosenblum & Schulman 1997).

The fabrication of inlays and onlays using the In-Ceram ceramic can be successfully made with the help of CAD/CAM technology. No clinical data are available on the performance of inlays and onlays utilizing the conventional technique.
2.4.4 Machinable ceramics

The development of the machinable technology took place in the 1980’s. At that time the application of this method was only indicated for the fabrication of inlays and onlays (Isenberg et al. 1992). Nowadays, machining has become a viable option as a forming method in the fabrication of all-ceramic restorations. Both CAD/CAM systems and the precision copy-milling machine are commercially available (Kelly et al. 1996).

2.4.4.1 CAD/CAM systems

- Cerec (Sirona, D-Bensheim)

The introduction of computer-aided design/computer-aided manufacture (CAD/CAM) systems to restorative dentistry represents a major technological breakthrough. This technology is implemented in the Cerec system, which was developed in 1984 (Mörmann & Bindl 2000). The system mills ceramic restorations from industrial blocks of ceramic material which are prefabricated under optimum and controlled conditions (Martin & Jedynakiewicz 1999). It is possible to obtain a high and uniform ceramic quality without the inevitable material variations seen in manually-produced restorations (Sjögren et al. 1992). It is possible with this system to generate a restoration without taking an impression, to fabricate a temporary restoration, and to avoid any laboratory assistance (chair side). The entire procedure can be preformed in one appointment. The annual failure rates of CAD/CAM ceramic inlays and onlays range from 0% to 4.4% (Hickel & Manhart 2001).

Technically, the cavity is coated with a light-reflecting powder, mapped stereophotogramatrically using a mini hand-held, 3-dimensional intraoral video camera (Sidexis/Sirocam 2, Sirona, Bensheim, D). This procedure is called optical impression (Mörmann & Brandestini 1989). The obtained information is fed to a computer that stores the 3-dimensional pattern depicted on the screen. The video display serves as a format for the necessary manual construction via an electrical signal. Then the integrated microprocessor develops the final 3-dimensional restoration from the 2-dimensional construction. After that the electronic information
is transferred numerically to the linked miniature 3-axis milling device. The milling unit driven by a water turbine device generates a restoration from the standard ceramic block. The blocks are cast and cerammed by several manufacturers (Mörmann & Bindl 2000).

The available types of ceramic blocks are as follows:

**Cerec Vitablocs Mark I** (Vita Zahnfabrik, D-Bad Säckingen)

The ceramic material of these blocks is a feldspathic porcelain with a fracture strength of 93 MPa and a hardness similar to that of conventional feldspathic porcelain (Rosenblum & Schulman 1997). This material was the first composition used with the Cerec system. It is recommended for the fabrication of veneers, inlays/onlays and single crowns (Otto 1995).

**Cerec Vitablocs Mark II** (Vita Zahnfabrik, D-Bad Säckingen)

This is a feldspathic porcelain of increased strength (up to 152 MPa), and it has a finer grain size than the Mark I compositions. The hardness of the material is equal to that of tooth enamel (Rosenblum & Schulman 1997). The material is indicated for the fabrication of veneers, inlays/onlays and single crowns (Otto 1995).

**ProCAD** (Ivoclar-Vivadent, FL-Schaan)

It is a leucite reinforced glass ceramic with a fracture strength of 140-200 MPa which also indicates it for the fabrication of inlays, onlays, and single crowns (Gaglio 2001). No data are available on the performance of inlays and onlays made out of this ceramic.

Since the introduction of the Cerec system, a large number of in-vitro and in-vivo studies have been published. Reiss & Walther (1991) reported that the survival rate of 426 Cerec inlays was 95% after observation period of 3 years. The main reasons for replacement were fractures and postoperative symptoms. In a longitudinal clinical study Walther *et al.* (1994) reported that the success rate for 1011 Cerec inlays was
95% after 5 years. The main reasons for failure were either inlay, tooth fractures or caries. Otto (1995) reported a survival rate of 98% for 100 Cerec inlays after 5 years. In this study, 2 teeth required endodontic therapy. In a four-year follow-up Heymann et al. (1996) showed a survival rate of 100% for 19 Cerec inlays and 31 Dicor MGC inlays. Berg and Derand (1997) reported a survival rate of 94.1% for 51 Cerec I inlays after an observation period of 5 years. All inlays in this study showed marginal defects after 5 years. In a 7.5-year clinical trial, the survival rate of 1011 Cerec inlays was 91.6% (Reiss & Walther 1998). Premolars exhibited a better performance than molars. In another study, 36 inlays, made out of Cerec Vita Mark II blocks, have been observed for 3 years. Twenty eight inlays were luted with resin cement and 9 with glass-ionomer cement. Survival-rate results were 96.4% after 3 years for inlays luted with resin cement and 100% for inlays luted with glass-ionomer cement (Zuellig-Singer & Bryant 1998). In an 8-year follow-up clinical study, 32 Cerec inlays have been evaluated. Half of the inlays were fabricated from Vita Mark II block and the other half were fabricated from Dicor MGC blocks. Only 3 fractures were observed in this study (2 Dicor MGC and 1 Vitablocs Mark II) after 8 years and the survival rate was 90.6%. No difference was found between the two blocks used regarding degree of color matching, marginal integrity and general clinical performance (Pallesen & van Dijken 2000). Reiss & Walther (2000) reported a success rate of 90% for Cerec inlays after 10 years and 84.9% success rate after 12 years of observation. This study also showed that premolars exhibited a better performance than molars. In a short-term clinical study, 10 Cerec inlays were fabricated from Vitablocs Mark II. After two years, all onlays were recorded to be successful (Denissen et al. 2000). Unfortunately, no long-term clinical data are available on onlays using the Cerec technique.

2.4.4.2 Copy-milling technique

- **Celay** (Mikrona Technologies AG, CH-Spreitenbach)

The Celay technique is a variation of the direct-indirect restoration concept but without the need for a laboratory technician (Eidenbenz et al. 1994). After the tooth preparation is completed, a precision imprint composite material (Espe-Celay-Dent,
Espe, D-Seefeld) is molded directly in the cavity, where it is adjusted for occlusion, contact relations, and marginal integrity. The material then undergoes a light- or chemical curing process. Afterwards, it is removed from the cavity, and it serves as a prototype model to be copied and reproduced in ceramics using the milling system (Eidenbenz et al. 1994, Garber & Goldstein 1994). The milling center has two distinct aspects. In one part, the model to be copied is centered in a holder, where it is manually scanned. A second part of the milling machine contains a rotary turbine with various cutting tools. The directly-formed pattern in the vice is manually scanned with a sensor. This sensor is directly connected to the milling aspect. Any form scanned is thus simultaneously reproduced in all three dimensions in a block of ceramic by the rotary turbine. The gross form is developed with a diamond disc and refined with a diamond point. The same type of ceramic blocks that are available for the CAD/CAM systems can be used with this technique (van Dijken 1999). An appropriately-sized block is selected and inserted in the holder of the milling center. The system can also be used as a purely indirect process, in which an impression is made and a die fabricated in the laboratory. The composite resin imprint prototype material is precisely formed in the die to represent the desired restoration. The composite resin prototype inlay is then placed in the left side of the milling unit in a bipoint metallic vise. The surface of the prototype is then similarly scanned manually and reproduced in ceramic on the milling unit, which carves out an exact replica of the plastic prototype in ceramic. A thin white powder coating is used as a control of the tracing. Contact of the stylus will remove the white powder, and the blue color of the pre-inlay/onlay is visible. The occlusal scheme developed inside the oral cavity is reproduced identically, so that after completion of the milling process, the inlay is ready to be inserted with minor corrections. Additional characterization or colorization of the inlay can be accomplished in the laboratory by refiring the inlay prior to final finishing (Eidenbenz et al. 1994, Garber & Goldstein 1994).

An In-Ceram-like ceramic block (Alumina Celay Blank, Vita, D-Bad Säckingen) is also available for the Celay technique. The material is a feldspathic porcelain, in which a porous perform of alumina is manufactured under factory conditions.

Celay ceramic inlays were considered clinically acceptable by traditional criteria. Marginal fit was reported to differ slightly depending on whether the inlay pattern was fabricated directly on the prepared tooth or on a laboratory die (Siervo et al.
In only one clinical study 12 out of 15 Celay machined inlays survived after 3 years of function (Thordrup et al. 1999).

Both the Cerec and the Celay systems mill the ceramics with diamond burs, producing initially rough surfaces. It is the responsibility of the dentist to bring these surfaces to a high gloss with aluminum-oxide-coated flexible discs and felt cones impregnated with diamond particles to avoid wear of the opposing tooth (Roulet 1997a).

Two advantages are provided by the availability of CAD/CAM or other machining routes to all-ceramic restorations. Firstly, these systems remove the processing of ceramics, and hence microstructural control, from the dental laboratory and place it within jurisdiction of the manufacturer. Secondly, the manufacturer merely provides a few sizes of simple blocks; complex shaping is controlled by the machining process (Kelly et al. 1996).

2.4.4.3 Procera® all-ceramic system (Noble Biocare, S-Göteborg)

The Procera® all-ceramic system, which was developed in 1993, consists of a computer-controlled scanning and design station located in the dental laboratories that are connected via modem to Procera Scandivk AB in Stockholm, Sweden (Andersson & Oden 1993). The system is mainly indicated for the fabrication of all-ceramic crowns and abutments for single tooth restorations (Andersson et al. 1998). The restoration is composed of a densely sintered, high-purity aluminum oxide coping that is combined with low-fusing AllCeram® (Noble Biocare, S-Göteborg) veneering porcelain. The fabrication of the coping takes into account the sintering shrinkage of approximately 20% by enlarging a model of the preparation that is used in the manufacturing process. The scanner, which is located in a local dental laboratory, digitizes a conventional die. The digital image is sent by the modem to the central production unit, where the computer-controlled milling machines fabricate refractory dies compensating for the sintering shrinkage. The high-purity aluminum oxide powder (>99.5%) is compacted against the enlarged preparation model, milled, and sintered to full density (Andersson et al. 1998). The coping material has a flexural strength of 678 MPa (Ottl et al. 2000). The high-purity aluminum oxide system promotes the densification of alumina during melting and solidification,
hence eliminating most porosities and increasing the strength of the material (Andersson & Oden 1993).

Denissen et al. (2000) evaluated 7 Procera onlays after 2 years of clinical function. They had a survival rate of 100%. The average marginal gap width for the onlays was 68 µm. The authors reported that fabricating onlays using this technique is difficult due to problems faced when trying to do the surface measurements by the Procera contact probe. The orientation of the sapphire tip toward the preparation surface was reported to be critical. It was necessary to apply wax to smooth internal edges and make it easier for scanning the dies.

2.5 Occlusal forces affecting posterior restorations

Occlusal forces are forces created by the dynamic action of the muscles during the physiologic act of mastication. The bite forces increase with growth. Men bite with greater force compared to women. This difference between sexes is due to the fact that men have bigger muscles than women. It has been reported that there is a positive correlation between the maximal bite force in the incisor region and the vertical proportions of the anterior facial morphology; subjects with a high bite force have a relatively short lower anterior height. Higher biting loads are measured on molar teeth than on other teeth in the dental arch. No relation was found between facial characteristics and the maximal bite force in the molar region or the maximal bite force endurance (Kiliaridis et al. 1993). Published data on bite forces indicate that the maximum biting force that may occur in the posterior dental area vary between 300 and 880 N. (Bates et al. 1976, Gibbs et al. 1986, Kiliaridis et al. 1993). Some bruxers and clenchers presented biting forces that are six times higher than that of non bruxers. It was also reported that the maximum chewing forces in the molar region are approximately 400 N (Schwickerath & Coca 1987). It has been suggested that a force of 500 N, as used for cracking a hazelnut, seems to be the maximum limit for natural teeth (Kappert 1996). Thus, it can be concluded that in order to achieve a good clinical long-term result, it is important for the posterior restorations to be able to withstand the maximum stress created in this region.

When comparing the maximal biting forces exerted by the stomatognathic system, it is obvious that average functional chewing forces are lesser. It has been reported by
several authors that the normal physiological chewing forces around posterior teeth range from 2 to 150 N (Eichner 1963, Bates et al. 1976, De Boever et al. 1978, Jäger 1989). In several simulated clinical conditions, a load of 49 N is set for the chewing simulator to imitate the physiological biting force (Krejci et al. 1990, Behr et al. 1999, Kern et al. 1999).

### 2.5 Fracture strength test data of ceramic inlays and onlays

Fracture strength values are often relied upon as indicators of structural performance for brittle dental materials. However, strength is more of a conditional than an inherent material property, and strength data alone cannot be directly extrapolated to predict structural performance.

Extrapolation of strength data of clinical performance, considered alone, must be approached cautiously. Proper use of strength data for predicting the life expectancy of restorations in clinical situations requires knowledge of the following; (1) that the critical flaw in the test specimen is the same as the one involved in clinical failure; (2) that environmental influences have been replicated in the laboratory; (3) that failure parameters describing the flaw size, distribution, and crack growth rates have been measured; and (4) that stress distribution in the clinical structure is well characterized (Kelly 1995).

Typically, the fracture strength of ceramics is checked by using bend bars with three or four point loading and/or discs tested in biaxial flexure (Campbell 1989, Giordano et al. 1995b, Seghi & Sorensen 1995). Measured strengths vary as a function of specimen preparation and testing methodology, including surface condition, three-point versus four-point bending and different stress rates.

Homogeneous all-ceramic restorations consist of a layer of ceramic (approximately 1.0-2.0 mm thick) atop a layer of cement (approximately 30 to 120 µm thick) supported by a layer of dentin. This structure is not well represented by simple bar-shaped specimens, such as those used in 3-point or 4-point bending tests (Kelly 1999). Furthermore, the surface of a restoration is sophisticated and not represented by the typical test methods. Therefore, in order for strength testing to be relevant, it
is generally recommended that the mode of loading be chosen to closely simulate the actual component in service (Ritter 1995a, Kelly 1999).

While most laboratory studies have evaluated the strength of all-ceramic crowns and bridges placed on plastic abutments, metal abutments or natural abutments, only few studies tested the strength of all-ceramic inlays and onlays:

Dietschi et al. (1990) compared the fracture strength of natural teeth restored with inlays made out of Vitadur N and inlays made out of Ceramco II and luted with composite resin cement. Results of the fracture strength test for natural teeth (control), Vitadur N and Ceramco II all-ceramic inlays were 3547 N, 2680 N and 1662 N, respectively.

Esquivel-Upshaw et al. (2001) compared the fracture resistance of metal-ceramic inlays made of Goldtech Bio 2000 metal and Ceramco porcelain with Empress 2 all-ceramic inlays. The inlay preparation was made on 60 plastic teeth, with 30 teeth allocated for metal-ceramic inlays and 30 teeth for all-ceramic inlays. Each group was further divided into 5°-, 10°-, and 20-degree taper preparation. The mean fracture load for Empress 2 inlays and metal-ceramic inlays at 5°, 10°, and 20° was 70 N, 48 N, 33 N, and 40 N, 29 N, and 14 N, respectively.

2.7 Factors responsible for the failure of all-ceramic restorations

2.7.1 Microstructure of ceramics

It is well known that fractures always progress from the area that is subjected to the highest tensile stress. Porosities and microcracks have been shown to be sites of fracture initiation (van Dijken 1999). They can considerably increase internal stress, which initiates a crack that progresses from the inner surface and finally damages the restoration (Anusavice & Hojjatie 1992, Peters et al. 1993, van Dijken 1999). The initial cracks may form during processing, due to incomplete densification, which leaves angular pores behind, or due to differences in thermal expansion or a modulus between grains or inclusion particles (Jung et al. 2000). They also frequently form in the surface of ceramics through abrasion by abrasive particles or
corrosion by water (Kelly 1995). These cracks, coupled with a low fracture toughness, not only limit the strength of ceramics but also cause variation in strength and a time-dependency (Ritter 1995b). Most all-ceramic single restorations fail from the inner aspect outward (Kelly et al. 1990, Thompson et al. 1994, White et al. 1996, Kelly 1999), indicating that the interface is both a location of high tensile stress and an important source of flaws (Kelly 1995).

### 2.7.2 Thickness and surface roughness of ceramics

The thickness of a ceramic restoration can also affect fracture resistance. Under normal circumstances, a thick ceramic restoration would be assumed to demonstrate a higher degree of fracture resistance than a thin one (Tsai et al. 1998). Unfortunately, this relationship between the thickness of ceramic material and its susceptibility or resistance has not been examined conclusively.

It has been shown that roughness produced by the finishing procedure and the introduction of surface flaws may be accompanied by a reduction in strength of ceramic restorations. This was demonstrated by Williamson et al. (1996). They found that specimens with a coarsely ground surface were significantly weaker than those with polished surfaces. Giordano et al. (1994, 1995a) have reported that sequential polishing significantly improved the flexural strength of feldspathic porcelain. A similar effect has been demonstrated in an experimental study, where biaxial flexural strength of different ceramic materials was measured with and without glazing. A significant correlation was found between the roughness of the surface and the biaxial flexural strength: the smoother the surface, the stronger the sample. This correlation, however, couldn’t be found where the ceramic material had an inner structure which caused an even larger stress concentration than that caused by the combination of surface roughness and flaws (De Jager et al. 2000).

### 2.7.3 Oral environment

In the oral environment, the influence of water and changing temperature, called stress corrosion, can promote crack propagation and decrease the fracture strength of an all-ceramic restoration (Kelly 1995). In-vitro investigations showed that storage
in water for extended periods and/or changing temperature will alter the failure load data (Schwickerath 1986, Mante et al. 1993, Kern et al. 1994)

2.7.4 Parafunctional loads

Posterior teeth are loaded vertically during centric occlusion. Eccentric or parafunctional forces can increase the shear resistance of the ceramic material, thereby accelerating their fatigue rate (Hojjatie & Anusavice 1990). The intensity and duration of loading may have more influence on the fracture strength of single all-ceramic posterior restorations than the previous eccentric forces. However, the vertically-loaded all-ceramic restorations can withstand greater chewing forces; therefore, it would seem that they might have a better prognosis than restorations loaded more horizontally (Kelly 1999, Cotert et al. 2001).

2.7.5 Cementation methods of ceramic materials

In vivo, the forces of occlusion applied to the enamel surface create stresses that are transferred through the dentino-enamel junction to the supporting dentin where they are effectively distributed and absorbed. The transfer and distribution of stresses in an efficient manner are probably of equal importance to strength and toughness in a restorative system (Banks 1990).

The enamel of natural teeth has the greatest surface toughness. Its flexural-, and crack-formation strength equal 20 MPa and 1 MPa.m$^{1/2}$, respectively, whereas dentin has 80 MPa flexural strength and 3 MPa.m$^{1/2}$ crack-formation strength. These values are comparable to those of the weakest all-ceramic materials (Kappert & Krah 2001). The system dentin-enamel obtains its strength from the cohesive force between the two components that have values ranging from 10 to 30 MPa (Roulet 1997a, Kappert & Krah 2001). Therefore, the adhesion strength value between all-ceramic restoration and tooth structure should be more than 10 MPa (Kappert & Krah 2001).

Ceramic materials demonstrate a low tensile and shear resistance. Therefore, the fracture load of ceramic restorations depends on the cementation method. The first
all-ceramic restorative materials used in the posterior part of the mouth relied on conventional zinc phosphate cements and, later, on glass ionomer cements for retention (Banks 1990). In-vitro studies have shown that the fracture strength of all-ceramic restorations, which have been placed with the adhesive technique, is significantly greater than that of restorations placed with the conventional technique using phosphate or glass ionomer cements (Burke 1995, Burke et al. 2002). Based on the knowledge of microcrack formation, the internal surface of all-ceramic crowns has to be etched and coated with a polymer. This layer significantly helps to increase the strength of the restoration, as microcracks and small defects are covered (Rosenstiel et al. 1993). Non-reinforced ceramic materials exhibit very low fracture resistance. The pretreated dentin, in conjunction with the bonding medium, provides the ceramic restoration with the necessary strength. A bonding medium, which has a modulus of elasticity similar to that of dentin, can increase fracture resistance because the stress is reduced (Platt 1999). The elimination, blunting, or bridging of cracks may cause this strengthening effect, or a coating may act to reduce the ability of water to be transported to the crack tip, which lessens the stress-corrosion. Furthermore, polymerization shrinkage may actually increase the strength of all-ceramic restorations by creating compressive stresses within the ceramic (Magne et al. 1999, Platt 1999). Chemical bonding using hydrophobic silane treatments, has been shown to significantly increase the strength of feldspathic dental porcelain (Rosenstiel et al. 1993).

Two groups of dentinal adhesions are available: glass ionomer cements (Wilson & McLean 1988, Croll 1993) and dentin bonding agents together with resin composites (Krejci et al. 1993, Retief et al. 1993).

Glass ionomer cements are hybrids of silicate and polycarboxylate cements designed to combine the optical and fluoride-releasing properties of silicate particles. Compared to the extremely acidic matrix of silicate cement, glass ionomer cements have chemically-adhesive and more biocompatible characteristics of the polyacrylic acid matrix (Sturdevant et al. 1999). It has been found that glass ionomer cements have some disadvantageous physical properties, controversial biocompatibility and insufficient adhesion to porcelain (Moscovich et al. 1998).
Light-cured resin-modified glass ionomers (RMGIC) were developed to combine some advantages of glass ionomers and composite resins (Thonemann et al. 1995, Moscovich et al. 1998). These materials have a variety of different chemistries and setting behaviors (Thonemann et al. 1995). The mechanical properties of RMGICs, compared to the conventional glass ionomer cements, have been improved (Crim 1993, Croll 1993). RMGICs have been used as lining materials and as luting materials for composite or ceramic inlays (Thonemann et al. 1995). Platt (1999) have reported that RMGIC/ compomer has a hygroscopic expansion, which leads to failure of all-ceramic crowns when the material is used for both build-up or adhesive luting.

Glass ionomers, RMGICs or compomers are now acceptable only for use as a filler, because they are too weak (Christensen 1996b, Burke et al. 2002).

Nowadays, adhesive luting, using resin cements along with dentin bonding agents, is highly recommended to improve survival rate and fracture strength of all-ceramic inlays and onlays (Roulet 1997a, van Dijken et al. 1998, Kappert & Krah 2001, Burke et al. 2002)

2.8 Guidelines for ceramic inlay and onlay preparation

Many advantages can be obtained by retaining as much as possible of the healthy tooth structure. This can best be achieved by using minimally-invasive tooth preparation. The general benefits of using inlay and onlay preparations can be summarized as follows: (Braunwarth & Hellge 1991)

- Preserving healthy tooth structure.
- Facilitating superior periodontal health.
- Facilitating cementation without hydrolic behavior.
- Preserving the pulp’s health.
- Preserving the anatomical shape.
- Facilitating visual margin control.
- Facilitating efficient and effective oral hygiene for the patient.
- Improving testing of the tooth’s vitality.
The principles of cavity preparation designs for tooth-colored inlays and onlays are different from those for cast metal ones (Banks 1990, Jackson & Ferguson 1990, Hickel & Manhart 2001). Two requirements should be considered: (1) provide an adequate thickness for the restoration and (2) create a passive seating pattern (Ritter & Baratieri 1999).

The recommended preparation design for tooth-colored inlays and onlays is as follows: The walls should be divergent with up to 15°. All internal line angles should be rounded with a chamfer proximal box margin and no bevels. The depth should be 1.5 mm to 2 mm (Banks 1990, Jackson & Ferguson 1990, Lehmann & Hellwig 1998). The isthmus width should be 2 mm. For onlays, cusps should be reduced at least 1.5 mm (Banks 1990, Jackson & Ferguson 1990).

Some clinicians prefer to use the classical preparation form, as described for the metal partial crowns, which consists of an MOD box form retention with a modified finishing line in the shape of a shoulder with a rounded internal line angle (Banks 1990, Lehmann & Hellwig 1998). Because of the introduction of new generations of dentin bonding agents and composite resin cements, other preparation designs, which have less or no retention form, were suggested (Broderson 1994, Freedman 1998, King & Aboush 1999, van Dijken et al. 2001).

2.9 Factors that influence longevity of ceramic inlays and onlays

Factors that affect the survival rate of all-ceramic inlays and onlays can be divided into patient-related and processing- or operator-related factors (Hickel & Manhart 2001):

Patient-related factors include:
- Oral hygiene
- Preventive measures
- Compliance during recall
- Oral environment (quality of tooth structure, saliva, etc.)
- Size, shape, location of the lesion and tooth (number of surfaces, vital versus nonvital tooth, premolar versus molar)
- Cooperation during treatment
- Bruxism
- Habits (high sugar intake, smoking, frequent chewing of hard foods, etc.)
- Participation in contact sports

Processing- and Operator-related factors include:
- Correct indication
- Cavity preparation (size, type, finishing)
- Impression technique
- Handling and application
- Correct occlusion
- Experience (with material and technique)
- Recall schedule

### 2.10 Survival rate of ceramic inlays and onlays

The longevity of a dental restoration is an important concern. Informed insight into the longevity of these restorations is best provided by longitudinal studies (Leempoel et al. 1989, Hickel & Manhart 2001, Blatz 2002). Any prosthetic restorative system can be considered successful if it demonstrates a clinical survival rate of 95% after 5 years and 85% after 10 years (Pröbster 1996).

The survival rates of all-ceramic inlays and onlays with an observation periods of 5 years and longer are listed in table (2.2):
<table>
<thead>
<tr>
<th>Author (year)</th>
<th>Observation period (y)</th>
<th>Material</th>
<th>Type (No. of restorations)</th>
<th>Survival rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mörmann &amp; Krejci (1992)</td>
<td>5</td>
<td>Cerec Vita Mk I &amp; II</td>
<td>Inlays (8)</td>
<td>100</td>
</tr>
<tr>
<td>Walther et al. (1994)</td>
<td>5*</td>
<td>Cerec Vita blocks</td>
<td>Inlays (1011)</td>
<td>95</td>
</tr>
<tr>
<td>Hofman et al. (1995)</td>
<td>5</td>
<td>Cerec Vita blocks</td>
<td>Inlays (59)</td>
<td>90</td>
</tr>
<tr>
<td>Otto (1995)</td>
<td>5</td>
<td>Cerec Vita blocks</td>
<td>Inlays (100)</td>
<td>98</td>
</tr>
<tr>
<td>Berg &amp; Derand (1997)</td>
<td>5</td>
<td>Cerec I</td>
<td>Inlays (51)</td>
<td>94.1</td>
</tr>
<tr>
<td>Roulet (1997b)</td>
<td>6*</td>
<td>Dicor</td>
<td>Inlays (123)</td>
<td>76</td>
</tr>
<tr>
<td>Felden et al. (1998)</td>
<td>7*</td>
<td>Dicor, Empress, Mirage II, Cerec Vita Mark I, Duceram LFC</td>
<td>Inlays &amp; onlays (287)</td>
<td>94.2</td>
</tr>
<tr>
<td>Hayashi et al. (1998)</td>
<td>6</td>
<td>Fired ceramic</td>
<td>Inlays (49)</td>
<td>92</td>
</tr>
<tr>
<td>Lehner et al. (1998)</td>
<td>6*</td>
<td>Empress</td>
<td>Inlays &amp; onlays (138/ 17)</td>
<td>94.9</td>
</tr>
<tr>
<td>Reiss &amp; Walther (1998)</td>
<td>7.5*</td>
<td>Cerec Vita blocks</td>
<td>Inlays (1011)</td>
<td>91.6</td>
</tr>
<tr>
<td>Sjögern et al. (1998)</td>
<td>5</td>
<td>Cerec (chemical cure)</td>
<td>Inlays (33)</td>
<td>94</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cerec (dual cure)</td>
<td>Inlays (33)</td>
<td>85</td>
</tr>
<tr>
<td>Van Dijken et al. (1998)</td>
<td>6</td>
<td>Mirage (resin cement)</td>
<td>Inlays (58)</td>
<td>88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mirage (GI cement)</td>
<td>Inlays (57)</td>
<td>74</td>
</tr>
<tr>
<td>Fuzzi &amp; Rappelli (1999)</td>
<td>10*</td>
<td>Fired ceramic</td>
<td>Inlays (182)</td>
<td>97</td>
</tr>
<tr>
<td>Molin &amp; Karlsson (2000)</td>
<td>5</td>
<td>Mirage Cerec IPS Empress</td>
<td>Inlays (60)</td>
<td>92</td>
</tr>
<tr>
<td>Pallesen &amp; van Dijken (2000)</td>
<td>8</td>
<td>Cerec Vita MK II Dicor MGC</td>
<td>Inlays (16)</td>
<td>90.6</td>
</tr>
<tr>
<td>Reiss &amp; Walther (2000)</td>
<td>10</td>
<td>Cerec Vita blocks</td>
<td>Inlays (1010)</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>12*</td>
<td>Cerec Vita blocks</td>
<td>Inlays (16)</td>
<td>84.9</td>
</tr>
<tr>
<td>Thordrup et al. (2001)</td>
<td>5</td>
<td>Cerec Cos 2.0</td>
<td>Inlays (15)</td>
<td>92.9</td>
</tr>
<tr>
<td>Van Dijken et al. (2001)</td>
<td>5</td>
<td>IPS Empress</td>
<td>Onlays (182)</td>
<td>92.9</td>
</tr>
</tbody>
</table>

* Estimated survival (Kaplan-Meier analysis)

Table (2.2) Survival rates of all-ceramic inlays and onlays

These studies illustrate that the survival rate of all-ceramic inlays and onlays ranges between 74% to 100% with observation periods of up to 12 years. With the exception of two studies (Roulet 1997b, van Dijken et al. 1998), all other studies
showed very good clinical successes. Long-term clinical success of all-ceramic onlays was evaluated in only 4 studies (Felden et al. 1998, Lehner et al. 1998, van Dijken et al. 2001). Other studies with shorter observation periods between 2 to 4.4 years have evaluated all-ceramic onlays and reported good results as well (Tidehag & Gunne 1995, Studer et al. 1996, Fradeani et al. 1997, Denissen et al. 2000).
3. **Aim of the study**

The aim of this in-vitro study was to evaluate the survival rate and fracture strength of ceramic onlays fabricated out of an Experimental Heat-Press All-Ceramic material (EPC) with different preparation designs luted on upper first molars after exposure to the artificial mouth, and to compare the data with ceramic inlays and unprepared teeth (control).
4. **Outline of the study** (Fig. 4.1)

Ninety-six human upper molars were used for the experiment. They were randomly divided into one control group and 5 test groups, using sixteen samples of each (A-F). In the control group A, teeth were left with no preparation. In group B, inlay preparations were made (6° MOD taper box, 3 mm deep). The isthmus was 3 mm wide. A mesial and distal finishing 1 mm above the cemento-enamel junction was made. In group C, teeth were prepared in the same manner as described for group B, but in addition, the mesio-palatal cusps were reduced 2 mm with 45° on the occlusal plane, and the margins were left in an overlapping form. In group D, teeth were prepared in the same manner as in group B, and both palatal cusps were reduced 2 mm with 45° on the horizontal plane. In group E, teeth were prepared in the same manner as described for group B, then the palatal and disto-buccal cusps were reduced 2 mm with 45° on the horizontal plane. In group F, teeth were prepared in the same manner as in group B, then all cusps were reduced. Sixteen all-ceramic inlays and 64 onlays were fabricated out of an Experimental Press-Ceramic (EPC) material and adhesively luted. Afterwards, all of the samples, along with the control group, were placed in the artificial mouth for 1.2 million cycles. Then all samples were loaded in the universal testing machine until fracture occurred.

![Fig. (4.1) Outline of the study](image-url)
5. Materials and methods

5.1 Materials

5.1.1 Experiment teeth

Ninety-six caries-free human upper molars were used for the experiment. The teeth were obtained directly after extraction, cleaned and stored in 0.1% thymol solution at room temperature throughout the study. All teeth were inspected with a 10X magnifying glass to detect cracks before including them in the study.

5.1.2 Materials used for the fabrication of ceramic inlays and onlays

EPC (Ivoclar-Vivadent AG, FL-Schaan) (Table 5.1)

The experimental press ceramic (EPC) consists of lithium disilicate glass and sintered apatite glass. The chemical basis of the material is the same as the chemical basis of IPS Empress® 2 (Si₂O – Li₂O).

According to the manufacturer, these 2 different glass ceramic materials exhibit substantially improved physical properties and higher translucency. The framework is a lithium disilicate glass in which the glass layer is a new type of fluoroapatite porcelain. The framework material, representing the high strength component of the system, is pressed in the EP 500 press furnace (Ivoclar-Vivadent AG, FL-Schaan) at 910-920 °C. The crystalline phase of the material consists of elongated lithium disilicate crystals, measuring approximately 0.5 to 4 µm in length, and small lithium orthophosphate crystals (Li₃PO₄).

The glass layer is fired on the lithium disilicate framework at 740 °C. This sintering temperature is lower than the one needed for sintering the glass layer of IPS Empress® 2 (Table 5.2). The crystalline phase of the glass layer enhances the biocompatibility of the material. Additionally, the glass layer is responsible for
excellent aesthetics because it guarantees translucency, brightness and light scattering.

<table>
<thead>
<tr>
<th>Components</th>
<th>ma. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO\textsubscript{2}</td>
<td>57 – 80</td>
</tr>
<tr>
<td>Al\textsubscript{2}O\textsubscript{3}</td>
<td>0 – 5</td>
</tr>
<tr>
<td>La\textsubscript{2}O\textsubscript{3}</td>
<td>0.1 – 6</td>
</tr>
<tr>
<td>MgO</td>
<td>0 – 5</td>
</tr>
<tr>
<td>ZnO</td>
<td>0 – 8</td>
</tr>
<tr>
<td>K\textsubscript{2}O</td>
<td>0 – 13</td>
</tr>
<tr>
<td>Li\textsubscript{2}O</td>
<td>11 – 19</td>
</tr>
<tr>
<td>P\textsubscript{2}O\textsubscript{5}</td>
<td>0 – 11</td>
</tr>
<tr>
<td>Additional ingredients</td>
<td>0 – 8</td>
</tr>
</tbody>
</table>

**Table 5.1** Composition of EPC

<table>
<thead>
<tr>
<th>Properties</th>
<th>EPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical:</td>
<td></td>
</tr>
<tr>
<td>● Flexural strength</td>
<td>525 ± 75 MPa</td>
</tr>
<tr>
<td>● Fracture toughness</td>
<td>3.0 ± 0.5 MPa • m\textsuperscript{0.5}</td>
</tr>
<tr>
<td>Optical:</td>
<td></td>
</tr>
<tr>
<td>● Translucency</td>
<td>Very high translucency, similar to the natural tooth</td>
</tr>
<tr>
<td>Thermal:</td>
<td></td>
</tr>
<tr>
<td>● Coefficient of thermal expansion</td>
<td>10.6 ± 0.5 • 10\textsuperscript{-6} K\textsuperscript{-1} m/m</td>
</tr>
<tr>
<td>Chemical:</td>
<td></td>
</tr>
<tr>
<td>● Solubility</td>
<td>&lt; 100 µg/cm\textsuperscript{2}</td>
</tr>
<tr>
<td>Technical:</td>
<td></td>
</tr>
<tr>
<td>● Press temperature</td>
<td>920 °C</td>
</tr>
<tr>
<td>● Firing temperature of sinter ceramic resp.</td>
<td>800 °C</td>
</tr>
<tr>
<td>sinter glass ceramic (Dentin and Incisal)</td>
<td>(new type of material: 740 °C)</td>
</tr>
</tbody>
</table>

**Table 5.2** Properties and technical data of EPC (Information obtained from manufacturer)
5.1.3 Materials used in cementation procedures

**Variolink® II** (Ivoclar-Vivadent AG, FL-Schaan) (Table 5.3)

The Variolink® system is a micro-filled light/dual curing adhesive luting composites. It is available in 5 shades, 3 degrees of translucency, as well as 3 consistencies (low viscosity, high viscosity, and ultra-high viscosity for application of the ultrasonic technique). Barium glass is used as a filler in this system. It demonstrates excellent radiopacity and permits a clear distinction between the restoration, the cement and caries on X-rays.

Variolink® II is indicated for the adhesive cementation of all-ceramic, Ceromer, and composite restorations and is especially recommended by the manufacturer for the placement of IPS Empress® all-ceramic and Targis/Vectris Ceromer/FRC restorations.

<table>
<thead>
<tr>
<th></th>
<th>In weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Standard composition</strong></td>
<td><strong>Base</strong></td>
</tr>
<tr>
<td>Bis-GMA</td>
<td>13.1</td>
</tr>
<tr>
<td>Urethane dimethacrylate</td>
<td>6.6</td>
</tr>
<tr>
<td>Triethyleneglycol dimethacrylate</td>
<td>6.6</td>
</tr>
<tr>
<td>Barium glass filler, silanized</td>
<td>38.4</td>
</tr>
<tr>
<td>Ytterbiumtrifluoide (YbF₃)</td>
<td>25.0</td>
</tr>
<tr>
<td>Mixed oxide, silanized</td>
<td>5.0</td>
</tr>
<tr>
<td>Ba-Al-Fluoro-Silicate glass</td>
<td>5.0</td>
</tr>
<tr>
<td>Catalysts and Stabilizers</td>
<td>0.3</td>
</tr>
<tr>
<td>Pigments</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

*Table 5.3 Composition of Variolink® II*
Variolink® II professional set consists of:

**Total Etch**® is a gel for enamel etching and dentin conditioning. It contains phosphoric acid (37% wt. % in water), silicon dioxide and pigments.

**Syntac**® is a two-phase adhesive system, which mediates a chemically-stable bond between the composite and the tooth structure. Syntac primer is composed of polyethylene glycol dimethacrylate, maleic acid and ketone in an aqueous solution. Syntac adhesive is composed of polyethylene glycol dimethacrylate and glutaraldehyde in an aqueous solution. This system can be used with both light- and self-curing composites. A light-curing bonding agent (Heliobond®) must be used prior to application of the composite.

**Heliobond**® is a light-curing, single component bonding material for optimizing the enamel etching technique. It contains Bis-GMA 60% wt. and Triethylene glycol dimethacrylate 40% wt.

**Monobond S**® is a single-component material mediating a stable bond between the ceramic material and the composite. It contains a water/ethanol solution with acetic acid set to pH 4 (99% wt.) and 3-methacryloxypropyl-trimethoxysilane 1% wt.

**Liquid strip**® is a glycerine gel. It is impermeable to oxygen and therefore can be used for the try-in of the luting material and ceramic restorations.

**IPS Ceramic etching gel**® is a hydrofluoric acid that creates an excellent retentive etching pattern in the IPS Empress® 2 material.

### 5.1.4 Impression and die materials

**Dimension® Garant L** (Espe, D-Seefeld)

This is an additional hydrophilic low consistency polymerization silicone material which is recommended for impression taking for partial crowns, crowns and bridges.
This material presents 4.5% deformation under load (ISO), 99.9% elasticity after deformation (ISO), and –0.20% linear dimensional change (ISO, after 24 h). The setting time is 5½ minutes after mixing.

**Permagum® Putty Soft** (Espe, D-Seefeld)

It is an additional cross-linking high viscosity silicone impression material with a -0.05 % dimensional change and a 0.3% compression set. The mixing time is 45 seconds and the setting time is 5 minutes.

**GC Fujirock®** (GC, B-Brussel)

This is a type 4 dental stone with improved physical properties and workability. The recommended water/powder ratio is 20 ml/100g. The setting expansion is 0.08% and the compressive strength is 53 MPa.

### 5.1.5 Additional materials (Table 5.4)

<table>
<thead>
<tr>
<th>Material / Equipment</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anti-Rutsch Lack</td>
<td>Wenko-Wenselaar GmbH, D-Hilden</td>
</tr>
<tr>
<td>Artificial oral environment /Thermocycling system</td>
<td>Willytech, D-Munich / Gebrüder Haake GmbH, D-Karlsruhe</td>
</tr>
<tr>
<td>Steatite ceramic ball</td>
<td>Hoechst Ceram Tec, D-Wunsiedel</td>
</tr>
<tr>
<td>Technovit 4000</td>
<td>Kulzer, D-Wehrheim</td>
</tr>
<tr>
<td>Zwick Z010/TN2S</td>
<td>Zwick, D-Ulm</td>
</tr>
</tbody>
</table>

**Table 5.4** Additional materials
5.2 Methods

5.2.1 Experiment teeth

See outline of study.

5.2.2 Fabrication of models before preparation

Sample holders were made from small blocks of dental stone for the fabrication of models of the teeth before preparation. Two holes were bored into each block in order to fix the teeth inside. Two teeth were fixed inside each block using Formasil® Xact (Heraeus Kulzer GmbH, D-Wehrheim). Teeth were numbered, and the numbers were carved on the blocks using a burr and a hand piece. Afterwards, impressions were taken of the blocks containing the teeth using Dimension® Garant L (Espe, D-Seefeld), Permagum® Putty Soft (Espe, D-Seefeld) and perforated custom-made plastic trays (Minitrays, Hager & Werken GmbH, D-Duisburg) with the Putty-Soft-Wash-Technique. A thin layer of polyvinyl siloxane adhesive was applied on the tray. After 5 minutes, Dimension® Garant was applied around the tooth, and Permagum® Putty Soft was put on the tray. The tray was then placed parallel to the tooth line, and held without pressure until the impression material was set (approximately 7 minutes). Afterwards, the impression was removed from the teeth and one hour later the master model was poured. A silicon surfactant was used to avoid introducing bubbles into the model and then GC Fujirock® type 4 dental stone was mixed with water. The recommended water/powder ratio is 20 ml/100 g. The powder was added to the water within 10 seconds, then mixed uniformly for 60 seconds by mechanical spatulation under vacuum. After a setting time of at least 45 minutes, the model was removed from the impression and trimmed.

Creating the models before the preparation, assures that the final product will most closely resemble the original shape of the tooth.

5.2.3 Tooth preparation (see outline of study) (Fig. 5.1-7)

In group A, teeth were left with no preparation (control group).
Preparation for group B (Fig. 5.3 a & b)

A 6° taper box form, with rounded and soft internal line angles, was prepared to represent an MOD cavity. It was 3 mm deep and the isthmus was 3 mm wide. The mesial and distal finishing line was 1 mm above the cemento-enamel junction.

Preparation for group C (Fig. 5.2, 5.4 a & b)

Teeth were prepared in the same manner as in group B. In addition, the mesio-palatal cusps were reduced by 2 mm with an angle of 45° on the occlusal plane. The margins were left in an overlapping form without a bevel.

Preparation for group D (Fig. 5.1, 5.5 a & b)

Teeth were prepared in the same manner as group B. In addition, the palatal cusps were reduced by 2 mm with an angle of 45° on the occlusal plane and the margins were left in an overlapping form without a bevel.

Preparation for group E (Fig. 5.6 a & b)

Teeth were prepared in the same manner as group B. In addition, the palatal and disto-buccal cusps were reduced by 2 mm with an angle of 45° on the occlusal plane and the margins were left in an overlapping form without a bevel.

Preparation for group F (Fig. 5.7 a & b)

Teeth were prepared in the same manner as group B. In addition, both palatal and buccal cusps were reduced by 2 mm with an angle of 45° on the occlusal plane and the margins were left in an overlapping form without a bevel.
6° taper box form with internal rounded line angle

2mm reduction of the cusps (45°)

Mesial and distal finishing 1mm above the CEJ

Fig. 5.1 Preparation of group D

3mm isthmus width, finishing without bevels, rounded internal line angles

Fig. 5.2 Preparation of group C
Fig. 5.3 (a & b) Preparation of group B

Fig. 5.4 (a & b) Preparation of group C

Fig. 5.5 (a & b) Preparation of group D

Fig. 5.6 (a & b) Preparation of group E
5.2.4 Final impressions and fabrication of master models

The prepared teeth were fixed again inside the marked holders, which were already made for taking impressions before preparation. Impressions were taken with the same impression materials used before and with the Putty-Soft-Wash-Technique. After setting, the impressions were removed from the teeth, and one hour later the master models were poured. Both the same technique used for pouring models and the same dental stone (GC Fujirock® type 4) were used before preparation. After a setting time of at least 45 minutes, the models were removed from the impressions.

5.2.5 Fabrication of ceramic inlays and onlays (EPC)

All models before and after preparation from the different groups were sent to the manufacturer (Ivoclar-Vivadent AG, Schaan, FL), in order to fabricate the ceramic inlays and onlays. The following procedures were performed by the manufacturer:

A surface hardening agent (Margidur, Benzer Dental AG, Zurich, CH) was applied on the master models. Afterwards, one layer of dye spacer (Purargent, Benzer Dental AG, Zurich, CH) was painted on the inner surfaces of the dies, but only up to approximately 0.5 mm above the preparation margin.

Using the silicone key from the models before preparation as a guide, full wax-ups of the inlays and onlays were fabricated using dental wax (Pro Art Sculpturing Wax, Williams AG). The silicone keys were helpful in restoring the original surface structure of the teeth before preparation. A 3 mm round wax sprue was then
attached to each wax-up at an approximately 45° angle. The sprues had the following dimensions: round profile, 3-8 mm length, 2-3 mm diameter, 8 gauges. The investment was carried out with the IPS Empress® 2 Speed investment material. Each of the 4 pieces was invested together with a 200 g investment material. The investment was mixed with its liquid for 1 minute in a vacuum, according to instructions. After a setting time of one hour the ring gauge and ring base were removed with a turning movement, and the paper ring and rough spots on the bottom side of the investment cylinder were removed.

The investment ring was preheated without the ingot, but including the plunger, in a conventional preheating furnace (KaVo Type 5636, KaVo AG, D) beginning at room temperature and increasing to 850°C. Preheating the IPS Empress investment ring together with casting objects is not recommended, because oxides may settle in the investment ring. The following parameters were checked:

- Temperature increase (beginning at room temperature): 5°C per minute
- Final temperature: 850°C
- Holding time: 60 minutes at 850°C

The investment cylinder was then removed from the furnace and the corresponding cold ingot (EPC VP1989 / 4 g) was placed into the cylinder. The following press parameters were observed. (Table 5.5)

<table>
<thead>
<tr>
<th>P</th>
<th>B</th>
<th>t↑</th>
<th>T</th>
<th>H</th>
<th>V₁</th>
<th>V₂</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>700°C</td>
<td>60°C/min</td>
<td>915°C</td>
<td>20 min.</td>
<td>500 °C</td>
<td>915°C</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.5 Pressing parameters for EPC using the EP 500 / V2.9 press furnace

After setting the exact parameters, the investment cylinder with the ingot was placed in the center of the EP 500 / V2.9 press furnace. After manual closing of the furnace head the program was activated, and the press process ran automatically. An acoustic signal indicated the end of the pressing cycle.

The investment cylinders were removed from the press furnace after approximately 60 minutes. Due to the difference in the coefficient of thermal expansion of the
various materials, cylinders occasionally show cracks. These cracks do not compromise the results of the pressing. The investment cylinder was separated using a separating disc to create a predetermined breaking point. Rough divestment was carried out with sand particles at 2-bar pressure. Subsequently, the pressed frameworks were cleaned in Invex liquid (Ivoclar-Vivadent AG, FL-Schaan) in an ultrasonic unit for 10 minutes, rinsed with water, and blow dried. The white reaction layer was then removed with Al$_2$O$_3$ (type 100) at 1 bar pressure. The pressed frameworks were cut from the sprues using a fine diamond disc. The attachment points were removed with ceramic burs. The ceramic frameworks were cleaned with steam, dried with oil-free air, and fitted on the master models.

Subsequently, two glaze firings were performed in the Programat P 100 furnace (Ivoclar-Vivadent AG, FL-Schaan) using glazing liquid (Empress Universal Glasur C27688, Ivoclar-Vivadent AG, FL-Schaan). The following firing parameters were considered: (Table 5.6)

<table>
<thead>
<tr>
<th>P</th>
<th>B</th>
<th>t↑</th>
<th>T</th>
<th>S</th>
<th>H</th>
<th>V$_1$</th>
<th>V$_2$</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>403°C</td>
<td>60°C</td>
<td>770°C</td>
<td>6 min.</td>
<td>2min.</td>
<td>450°C</td>
<td>769°C</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.6 Firing parameters for EPC using the EP 500 / V2.9 press furnace

Then the fitting surfaces of the inlays and onlays were sandblasted with Al$_2$O$_3$ (type 100) at 1-bar pressure.

The finished ceramic inlays and onlays made out of EPC were delivered with the master models and the models pre-testing models.

5.2.6 Luting procedures

After 2 minutes of ultrasonic cleaning, each tooth was dipped in 96% alcohol. The inner surfaces of the restorations were etched for 20 seconds with IPS Ceramic etch gel, rinsed with water for 30 seconds and dried. Monobond S was then applied with a brush, and after 60 seconds, dried with air. Then Heliobond was applied with a brush and dispersed with air. All prepared teeth were cleaned using a prophylaxis paste (non-fluoride) with a rotary brush. The prepared teeth were etched with 37%
phosphoric acid for 30-60 seconds, and Syntac Primer was applied and dispersed with an air syringe after 15-20 seconds. Then Syntac Adhesive was applied and dispersed with air after 10 seconds. Afterwards, Heliobond was applied and dispersed with air. Variolink® II was mixed and applied to the inner surfaces of the inlays, onlays and prepared teeth and then the restorations were placed on the teeth and held in place on the central fossa of the restoration using a plastic stick and under finger pressure (approx. 10-15 N). Any excess cement was removed and glycerine gel was applied in the marginal area of the restorations. Then all surfaces of the restorations were light-cured for 1 minute occlusally, mesially, distally, lingually, and buccally.

After setting, test samples were cleaned using a prophylaxis paste (non-fluoride) with a rotary brush.

5.2.7 Artificial periodontal membrane

In order to imitate physiological tooth mobility, all roots of the selected teeth were covered with an artificial periodontal membrane made out of gum resin (0.25 mm thickness) (Anti-Rutsch-Lack, Wenko-Wenselaar GmbH, D-Hilden) (Kern et al. 1993). In order to conform to the biological width, each tooth was coronally covered with wax, 2 mm short of the cemento-enamel junction, and then dipped once in the gum resin. After the gum resin had dried, the excess resin on the root tip was removed using a scalpel so that a uniform coating remained on the root surface.

5.2.8 Preparing the representative model of a clinical case

An upper molar was selected as a representative model of a clinical case. The model was embedded in a sample holder of the artificial oral environment (Willytech, D-Munich) using a silicone putty material (Optosil®, Kulzer, D-Wehrheim). The occlusal surface of the sample was set to be parallel to the horizontal plane. A silicone mold of the representative model was then fabricated with a polysiloxane impression material (Putty Soft, D-Seefeld,) covering at least 2 mm above the edge of the sample holder. This silicone mold was then used as the negative form for fixing the test specimens in the sample holder.
5.2.9 Embedding the experiment teeth in the sample holders

Using wax, all teeth were fixed vertically at 90° into the silicone mold. The wax covered the whole crown, and it was extended 2 mm apically. The sample holder was then isolated with Vaseline (Weißes Vaseline, FL-Schaan) and attached to the prepared silicone mold with the tooth in place. Then self-curing polyester resin (Technovit 4000®, Kulzer, D-Wehrheim) was mixed and poured into the sample holder. After the resin had set, the silicone was removed, and the crowns of the teeth were cleaned.

5.3 Tests

5.3.1 Exposure of the test samples to the artificial mouth

(Fig. 5.8-11)

The artificial oral environment (Willytec, D-Munich) consists of eight identical sample chambers, two stepper motors controlling vertical and horizontal movement of the samples against the antagonist, a hot and cold water circulation system (Haake, D-Karlsruhe) and a computerized control unit (Kern et al. 1999). All of the samples in each group were subjected to 1,2 million cycles by a reproducible dynamic occlusal load. Instead of following the standard protocol of applying 49 N load (De Boever et al. 1978, Krejci et al. 1990), the applied load here was 98 N, and the thermo-cycling was 5°C to 55°C for 60 seconds each with an intermediate pause of 12 seconds, maintained by the thermostatically-controlled liquid circulator (Haake, D-Karlsruhe). A 6 mm in diameter ceramic antagonist Steatit® ball (Höchst Ceram Tec, D-Wunsiedel) was applied vertically onto the occlusal surface of the restorations.

All samples were examined twice a day. Fractures of the teeth or of the porcelain were recorded as a failure.
Test parameters of the artificial mouth (Table 5.7)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold/hot bath temperature</td>
<td>5 °C/55 °C</td>
</tr>
<tr>
<td>Dwell time</td>
<td>60 s</td>
</tr>
<tr>
<td>Vertical movement</td>
<td>6 mm</td>
</tr>
<tr>
<td>Horizontal movement</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Descending speed</td>
<td>60 mm/s</td>
</tr>
<tr>
<td>Rising speed</td>
<td>55 mm/s</td>
</tr>
<tr>
<td>Forward speed</td>
<td>60 mm/s</td>
</tr>
<tr>
<td>Backward speed</td>
<td>55 mm/s</td>
</tr>
<tr>
<td>Applied weight per sample</td>
<td>10 kg (98 N)</td>
</tr>
<tr>
<td>Cycle frequency</td>
<td>1.6 Hz</td>
</tr>
</tbody>
</table>

Table 5.7  Parameters used for the experiment in the artificial mouth

5.3.2 Fracture strength test (Fig. 5.13)

Using a universal-testing machine (Zwick, Z010/TN2S, D-Ulm), all samples were loaded until fracture occurred. A 1-mm thick tin foil was placed over the occlusal surface of the teeth to achieve homogenous stress distribution. A perpendicular load was applied to the occlusal surface of samples, under a stroke control of 2 mm/min. The loads required for fracturing the samples were recorded with the Zwick testXpert® V 7.1 software.

5.3.3 Statistics

Data after dynamic loading of the test samples in the artificial mouth were analyzed by the Kaplan-Meier method (survival rate).

The statistical analysis of the fracture strength tests was performed at the Institute of Medical Biometry and Medical Informatics, Albert Ludwigs University, Freiburg, Germany using pair-wise comparisons with the Wilcoxon test (Splus statistic program, version 3.4 release 1 for Sun SPARC) at a significance level 0.05.
Fig. 5.8 Schematic drawing of the dual-axis chewing simulator with eight sample chambers (Willytech, Munich, D) from Kern et al. 1999.

1) upper crossbeam, 2) lower crossbeam, 3a) water reservoir (in), 3b) water reservoir (out), 4) filter for cold water, 5) filter for warm water, 6) pump for removal of cold water, 7) pump for removal of warm water, 8) pump for application of cold water, 9) pump for application of warm water, 10) motor block, 11) table.

Fig. 5.9 Chewing simulator (Willytech, D-Munich)
Fig. 5.10 Schematic drawing of one chewing chamber (Kern et al. 1999).

Fig. 5.11 Sample in the chewing chamber

Fig. 5.12 Fracture strength test of a sample
6. Results

6.1 Survival rate of test samples after exposure to the artificial mouth

All the test samples survived 1,200,000 dynamic loading cycles and thermocycling in the artificial oral environment.

6.2 Fracture strength of the test samples (Table 6.1)

For each group, statistics were computed for fracture strength values after artificial aging. These results are represented in the box plot (Fig. 6.1).

The fracture strength values of all test samples after simulation in the artificial oral environment were over 800 N. The smallest value was observed in test group F (852.4 N), whereas the highest value was observed in the control group A (3616.0 N).

Results of the comparison of the fracture strengths of all test groups showed no statistically significant differences between different groups (Table 6.2).

<table>
<thead>
<tr>
<th>Group</th>
<th>Minimum</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; Quartile</th>
<th>Median</th>
<th>Mean</th>
<th>3&lt;sup&gt;rd&lt;/sup&gt; Quartile</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (control) : Natural teeth with no preparation</td>
<td>871.5</td>
<td>1480.0</td>
<td>1960.0</td>
<td>2041.0</td>
<td>2228.0</td>
<td>3616.0</td>
</tr>
<tr>
<td>B: MOD inlays</td>
<td>1023.0</td>
<td>1463</td>
<td>1567.0</td>
<td>1700</td>
<td>1948</td>
<td>2831.0</td>
</tr>
<tr>
<td>C: MOD with mesio-palatal cusp</td>
<td>880.7</td>
<td>1489.0</td>
<td>1870.0</td>
<td>1789.0</td>
<td>2116.0</td>
<td>2547.0</td>
</tr>
<tr>
<td>D: MOD with palatal cusps</td>
<td>858.4</td>
<td>1365.0</td>
<td>1687.0</td>
<td>1594.0</td>
<td>1789.0</td>
<td>2462.0</td>
</tr>
<tr>
<td>E: MOD with palatal and disto-buccal cusps</td>
<td>963</td>
<td>1577</td>
<td>1705</td>
<td>1836</td>
<td>2049</td>
<td>3486</td>
</tr>
<tr>
<td>F: MOD with palatal and buccal cusps</td>
<td>852.4</td>
<td>1306.0</td>
<td>1842.0</td>
<td>1796.0</td>
<td>2343.0</td>
<td>2612.0</td>
</tr>
</tbody>
</table>

Table 6.1 Statistical analysis of the fracture strength results in N (fracture strength of each sample is listed in the appendix)
Fig. 6.1 Box plot of the fracture strength test results in N.

The central box shows data between the 1 st -quartile and the 3 rd -quartile, the median is represented by a line. “Whiskers” represent the extremes of the data, and very extreme values are shown by themselves.

A= Natural teeth with no preparation
B= MOD Inlay preparation
C= MOD preparation with reduction of the mesio-palatal cusp
D= MOD preparation with reduction of palatal cusps
E= MOD preparation with reduction of palatal and disto-buccal cusps
F= MOD preparation with reduction of all cusps
Table 6.2: Results of the multiple pair-wise comparisons of the fracture strength of test groups after loading in the artificial oral environment using the Wilcoxon test (significantly different when value < 0.05)

<table>
<thead>
<tr>
<th>Wilcoxon test</th>
<th>Group A (control)</th>
<th>Group B</th>
<th>Group C</th>
<th>Group D</th>
<th>Group E</th>
<th>Group F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group A (control)</td>
<td>1.000</td>
<td>0.318</td>
<td>0.665</td>
<td>0.062</td>
<td>0.510</td>
<td>0.638</td>
</tr>
<tr>
<td>Group B</td>
<td>0.318</td>
<td>1.000</td>
<td>0.462</td>
<td>0.925</td>
<td>0.337</td>
<td>0.559</td>
</tr>
<tr>
<td>Group C</td>
<td>0.655</td>
<td>0.462</td>
<td>1.000</td>
<td>0.169</td>
<td>0.895</td>
<td>0.955</td>
</tr>
<tr>
<td>Group D</td>
<td>0.062</td>
<td>0.925</td>
<td>0.169</td>
<td>1.000</td>
<td>0.365</td>
<td>0.337</td>
</tr>
<tr>
<td>Group E</td>
<td>0.510</td>
<td>0.337</td>
<td>0.895</td>
<td>0.356</td>
<td>1.000</td>
<td>0.865</td>
</tr>
<tr>
<td>Group F</td>
<td>0.638</td>
<td>0.559</td>
<td>0.955</td>
<td>0.337</td>
<td>0.865</td>
<td>1.000</td>
</tr>
</tbody>
</table>

6.2 Fracture patterns of the test samples

**Group A (teeth with no preparation)** (Fig 6.2 a & b)

All test samples of the control group fractured in a homogenous manner. The fracture always initiated in the enamel where it had contact with the testing head in the crown. No root fractures were noticed.

**Group B** (Fig. 6.3 a, b, c)

Most samples fractured in a homogenous manner. No debonding of the ceramic restorations occurred. In only two test samples the teeth fractured with the restorations.
In most of the test samples, the fracture initiated in the restoration where it had contact with the testing head starting at the cement interface and extending towards the occlusal surface. In only one test sample, it was noticed that the crack initiation occurred externally at the approximal incline near the loading site.

**Group C**

Most samples fractured in a homogenous manner. No debonding of the ceramic restorations occurred. Fracture of the teeth with the restorations occurred in 4 test samples.

The fracture always occurred in the same manner as in group B. All fracture patterns went horizontally through the whole restoration surface (MOD). In only two test samples, the crack initiation was situated in the occlusal region of the external surface of the inlay near the occluso-axial line angle

**Group D**

Most samples fractured in a homogenous manner. No debonding of the ceramic restorations occurred. In three test samples the teeth fractured with the restorations.

The fracture always occurred in the same manner as in other groups. In only one test sample, it was noticed that the crack initiation occurred externally at the approximal incline near the loading site.

**Group E**

Most samples fractured in a fairly homogenous manner. No debonding of the ceramic restorations occurred. In only two test samples the teeth fractured with the restorations.

The fracture always occurred in the same manner as in other groups. All fracture patterns were going through the whole restoration (MOD). Crack initiation occurred at the occlusal surface in only one test sample.
**Group F** (Fig 6.4 a, b, c)

Most samples fractured in a homogenous manner. No debonding of the ceramic restorations occurred. In three test samples the teeth fractured with the restorations.

The fracture always occurred in the same manner as the fracture in group B. All fracture patterns went through the whole restoration (MOD). In only one test sample, did the crack initiation occur at the occlusal surface.

![Fracture pattern of group A (control)](image)

![Fracture pattern for group B](image)

![Fracture pattern of group F](image)
7. Discussion

7.1 Materials and methods

7.1.1 The use of natural teeth

Extracted human teeth were used in this study because their bonding characteristics, thermal conductivity, modulus of elasticity and strength are closer to the clinical situation than metal, plastic replicas or animal teeth. Attention was paid to the selection of teeth with comparable sizes. Teeth which were too big or too small, as well as teeth with caries, cracks or deformities, were discarded. The extracted teeth were stored in 0.1% thymol solution to prevent them from drying out and thereby becoming brittle (Helfer et al. 1972). This storage solution also inhibited microbial activity (Sparrius & Grossman 1989).

The fracture strength of ceramic inlays and onlays, placed on extracted natural teeth, was evaluated in several in vitro studies (Geurtsen et al. 1989, Dietschi et al. 1990, 1995, Krejci et al. 1993, Cotert et al. 2001).

Bovine teeth have also been used for testing the fracture strength of ceramics (Mesaros et al. 1994) and the bonding strength of luting materials (Hosoya & Tominaga 1999). Bovine teeth have similar bonding characteristics, modulus of elasticity and tensile strength to human teeth (Sano et al. 1994). However, because of their size, they are not used for fracture strength tests of inlays and onlays.

Metal samples offer other advantages. They have identical dimensions and physical properties. However, testing the fracture strength of inlays and onlays on metal samples is inappropriate because of the difficulties in preparing the test samples and because the elastic and bonding properties of these abutments cannot be compared to those of natural teeth. Moreover, metal abutments do not reproduce the actual force distribution that occurs on restorations cemented on natural teeth.

Plastic samples made out of resin have also been used for fracture strength testing of inlays and onlays (Esquivel-Upshaw et al. 2001). They have a modulus of
elasticity that is similar to human dentin and they can be etched with 34% phosphoric acid (Neiva et al. 1998). The disadvantages of plastic teeth are that resin materials tend to absorb water (Soderholm 1981) which will weaken the luting condition and thereby reduce the fracture strength value of the restorations. Moreover, the bonding characteristics cannot be simulated when using plastic teeth, because they do not consist of water and organic substances.

7.1.2 Artificial periodontal membrane

In the present study, a thin layer of gum resin (Anti-Rutsch-Lack ®) was painted on the roots of the teeth. This layer served to mimic the physiological mobility of teeth during chewing simulation and fracture strength testing. Kern et al. (1993) showed that, when using this method, the artificial tooth mobility under a force of 5 N was 100 ± 30 µm in the horizontal direction and 65 ± 21 µm in the vertical direction. These values are similar to the physiological tooth mobility as described by Mühlemann (1951).

In several studies, ceramic inlays and onlays were embedded directly into dental stone, resin or rigid metal before fracture strength testing was performed (Dietschi et al. 1990, 1995, Cotert et al. 2001, Esquivel-Upshaw et al. 2001).

It has been demonstrated that sample mobility is a decisive factor in the evaluation of fracture strength (Kelly 1995), and when a small amount of tooth rotation is allowed, failure of the restoration is more relevant to the clinical situation (Kelly et al. 1995).

7.1.3 Tooth preparation

Two mm is the recommended depth for a cavity in all-ceramic inlays and onlays (Banks 1990, Lehmann & Hellwig 1998). In this study, a depth of 3 mm was used in the preparation cavity at the occlusal portion.

In the MOD inlay preparation, a width of one third of the intercuspal distance is recommended for the occlusal portion of the preparation (Joynt et al. 1987). This value, which is usually 3 mm in molars, guarantees an adequate thickness for the
restorative material and does not weaken the tooth (Jackson & Ferguson 1990, Garber & Goldstein 1994, Cotert et al. 2001).

The interproximal finishing lines should extend into the facial and lingual embrasures for ease of finishing after bonding (Presern & Strub 1983, Christensen 1988, Banks 1990). For the width of the proximal portion of the cavity, one third of the total faciolingual distance is recommended (Joynt et al. 1987, Lehmann & Hellwig 1998, Cotert et al. 2001).

All teeth prepared for ceramic inlays or onlays should exhibit a smooth internal surface with rounded line and point angles to minimize stress-concentrating effects that can lead to crack propagation and failure of the restoration (Banks 1990, Garber & Goldstein 1994, Lehmann & Hellwig 1998, Denissen et al. 2000). The walls of the preparation should be slightly divergent to the occlusal between 5° to 15° to assure a properly fitted restoration and increase fracture resistance of both the restorative material and the tooth structure (Jackson 1999). Esquivel-Upshaw et al. (2001) compared the fracture resistance of metal-ceramic inlays made of Goldtech Bio 2000 metal and Ceramco porcelain with Empress® 2 all-ceramic inlays. The inlay preparation was made on 60 plastic teeth, with 30 teeth allocated for metal-ceramic inlays and 30 teeth for all-ceramic inlays. Each group was further divided into 5-, 10-, and 20-degree taper preparations. The mean fracture load for Empress® 2 inlays was significantly higher than that for metal-ceramic inlays, and inlays with a 5° taper were significantly more fracture resistant than those with a 20° taper.

The reduction of weak cusps not only lessens the risk of ceramic fractures, but also lessens the risk of problems such as hypersensitivity. A tendency towards a reduction in fracture frequency could be seen when weak cusps were protected by reducing them (Milleding et al. 1995). An approximately 1.5 to 2 mm of occlusal cusp reduction is recommended in the literature for ceramic onlays (Hobo & Iwata 1986, Malament & Grossman 1987, Malament 1988, Christensen 1988, Banks 1990, Jackson & Ferguson 1990, Garber & Goldstein 1994, Denissen et al. 2000).

The design of the marginal finish line of inlays or onlays can influence the prognosis of the restoration. Farah et al. (1977) studied the effect of cavity wall taper and margin preparation on stress distribution using finite element analysis. They found that inlays with 7° taper and no occlusal bevel had better stress distribution than
cavities with more taper or a longer bevel. Taleghani & Leinfelder (1987) advocated a butt joint preparation margin for inlays while Jensen et al. (1987) recommended a 0.5 mm bevel for inlay and onlay preparations.

In a recent finite element analysis study, onlay restorations with three different types of marginal finish lines, i.e., shoulder, chamfer and bevel, were subjected to vertical and horizontal load at three different sites. The results showed that horizontal forces acting on the restoration generated the highest tensile stresses (Abu-Hassan et al. 2000).

It can be concluded from the above-mentioned studies that preparing the margins with bevels or chamfers is not recommended when using all-ceramic restorations. Thin layers of ceramic material covering the bevels or thin chamfers cannot withstand stresses that form during chewing, can easily fracture and lead to failure of the restoration. Although shoulder preparation enhances the fracture resistance of ceramic inlays and onlays, it requires additional removal of healthy tooth structure. Moreover, the advances in luting and bonding procedures and the increased use of adhesive techniques result in less extensive tooth preparations. Therefore, shoulder preparation was avoided in this study in order to minimize tooth structure removal.

### 7.1.4 Adhesive cementation

In this study, a dual-cured resin cement was used to lute the restorations on the teeth. Several studies showed a strong enhancement of the fracture strength of all-ceramic restorations bonded to dies or teeth versus non bonded restorations.

In an in-vitro investigation, Dietschi et al. (1990) found that ceramic inlays cemented with composite resin were more resistant to fracture than those luted with glass ionomer, although no statistically significant difference was found.

Stenberg & Matsson (1993) reported a failure rate of 23% for 25 Dicor inlays luted with glass-ionomer cement after 2 years.

Van Dijken et al. (1998) evaluated 118 feldspathic ceramic inlays luted with dual-cured resin composite or glass ionomer cement (GIC) over a 6-year follow-up.
Twelve percent of the resin composite group and 26% of the GIC group were assessed as failures.

Mitchell et al. (1999) tested the fracture toughness of six different luting cements (four conventional glass-ionomer cements, one resin-modified glass ionomer and one resin cement), in order to determine their tendency to fail cohesively when loaded. The results indicated that the fracture toughness of the resin-modified glass-ionomer cement was greater than any of the four conventional glass-ionomer cements, and that the fracture toughness of the resin composite cement was significantly greater than any of the other cements tested.

It can be concluded from the above-mentioned studies that the adhesive luting of ceramic inlays and onlays using resin cements has a better prognosis than luting with other materials.

Resin luting cements are available as light-/ dual-cured systems, dual-cured systems, or chemical-cured systems. Although chemically cured resin cements harden sufficiently, they allow only a short working time, which can be stressful for the operator and lead to failures in cementation. The light-cured systems provide the benefit of controlled working time. Color is more easily controlled because no mixing of components is required and try-in without polymerization is possible. However, obtaining a thorough polymerization through ceramic materials is not always accomplished. The critical thickness of ceramic restorations for polymerization is 2-3 mm (Blackman et al. 1990, Platt 1999).

7.1.5 Clinical relevance and influence of the artificial mouth on the survival rate and fracture strength of ceramic onlays

Before performing in-vivo studies or applying new dental materials for clinical use, in-vitro tests are recommended in order to prove their applicability and performance. In-vitro tests can be performed in a short period of time and have the advantages of reproducibility and the possibility of standardizing the test parameters (Krejci & Lutz 1990, Kern et al. 1999). However, each in-vitro test represents only one approach to a clinical situation. The more closely a test simulates the clinical situation, the more clinically relevant the results (Krejci et al. 1990). In the past, different chewing
Simulators have been used to simulate clinical conditions and have saved evaluation time for inlays and onlays (Krejci & Lutz 1990, Krejci et al. 1993, Mehl et al. 1998, Behr et al. 1999). It has been shown that ceramic restorations accumulate damage during cyclic loading and thermocycling. The accumulated subsurface damage weakens the ceramic restorations and can cause clinical failures (Kelly 1999). Schwickerath (1996) reported that the flexural strength of In-Ceram, IPS Empress and Dicor ceramics was approximately 50% of the initial strength after 100,000-fatigue loading cycles. Intraoral occlusal forces create dynamic repetitive loading. Therefore, instead of monotonic static loading, it is more clinically relevant to test the specimens under physiological fatigue load in a chewing simulator, which will allow evaluation of the dental restorative systems under clinically relevant conditions (DeLong & Douglas 1983, Krejci et al. 1990, Kelly 1999). However, no data is available on the effect of cyclic and dynamic loading on the fracture strength of ceramic inlays and onlays.

Adding moisture and controlled temperature to the environment was found to be important when measuring the fracture or fatigue strength of dental ceramics. Exposure to water was found to affect the mechanical properties of all-ceramic restorations. Also, storage in water for extended periods has been shown to alter the failure of all-ceramic materials (Kelly 1999) and to weaken the bond strength (Roulet et al. 1995). Furthermore, temperature changes also lead to slow flaw propagation (Kelly 1999). Although some authors used a median temperature of 37°C for testing dental material in the artificial oral environment (Brantley et al. 1986, Kappert & Altvater 1991), most of the authors used temperatures varying from 5°C to 55°C for their tests (Kern & Thompson 1993, Kern et al. 1999). In this study temperatures varying from 5° to 55°C were used simultaneously with the cyclic loading. No studies are available on the effect of thermocycling on the fracture strength of ceramic inlays and onlays.

Clinical studies showed that humans have an average of 250,000 masticatory cycles per year (DeLong & Douglas 1983, Sakaguchi et al. 1986). Therefore, to simulate a service time of 5 years, about 1,200,000 masticatory cycles have to be performed in the chewing simulator (Krejci & Lutz 1990, Kern et al. 1999). The artificial chewing cycle in the artificial oral environment is designed to correspond as closely as possible to physiological conditions. The magnitude, duration and frequency of the
force applied in the artificial mouth are comparable to values reported in the literature (Bates et al. 1976, Bradley 1996).

In this study, balls made of Steatite (a ceramic enamel analogue) were used as antagonists for the test samples in the chewing machine. It has been shown that antagonists made out of enamel are not suitable for standardized wear tests, because they differ in morphology, microstructure and composition (Wassell et al. 1994b). Metals and composites are also not acceptable as antagonists (Krejci & Lutz 1990). The advantages of a Steatite antagonist are that it has a Vickers hardness that is very similar to enamel, and is accurate, reproducible and cost-effective (Wassell et al. 1994a, b).

The parameters used for the chewing machine were limited to the physiological values found in the literature. A cycle loading force of 49 N was used in several studies (Krejci & Lutz 1990, Kern et al. 1999). However, clinical studies showed that biting forces can easily exceed the 49 N loading force (Gibbs et al. 1986, Schwickerath & Coca 1987). Therefore, it is more realistic, for purposes of experimental design, to consider higher loading forces than the functional forces that arise during chewing or swallowing. In this study, a cycle loading force of 98 N was used in order to approach a clinical situation comparable to the posterior area of the dental arch. Unfortunately, no studies are available on the performance of ceramic inlays and onlays in the artificial mouth.

7.1.6 The clinical relevance of fracture strength tests

In the presented study, the fracture strength of molars and molars with ceramic inlays and onlays was evaluated after exposure to the artificial oral environment.

The physical properties and performance of newly-developed dental materials must be tested before they can be recommended for clinical use (Ritter 1995b). The traditional fracture strength tests (biaxial flexural tests or 3-, 4-point bending tests) cannot be used to predict the performance of a restoration in the mouth, because they do not simulate a clinical mode of failure (Kelly 1995, Ritter 1995a). Also, traditional fracture strength tests can fail from their edges during processing, raising the possibility that premature failures occur from the uncharacteristic processing
flaws (Kelly 1995). Therefore, in order for testing to be relevant, test specimens must have the same type and distribution of flaws as the target structure when placed into service (Kelly et al. 1995, Ritter 1995a, b).

Kelly (1999) questioned the relevance of traditional load-to-failure tests of all-ceramic restorations. He mentioned that the elementary beam theory cannot be used to examine a cemented full coverage restoration or to predict its clinical behavior. Homogeneous all-ceramic restorations consist of a layer of ceramic, a layer of cement and are supported by a thickness of dentin. This structure of different materials having different modulus of elasticity is not well represented by simple bar-shaped specimens, such as those used in 3-point or 4-point bending tests. These tests also do not create failure mechanisms seen in retrieved clinical specimens (Kelly 1999). Moreover, no conclusion regarding longevity of the restoration can be drawn from fracture strength results alone. Furthermore, water showed that it can act chemically at crack tips and decrease the strength of glass and ceramics. Temperature change also affects the fracture strength of those materials. (Kern et al. 1994)

For the strength test to accurately reflect the variability and time dependency of a ceramic component in service, the test environment must be the same as the service environment, and the strength-controlling flaw population must be the same as that responsible for failure in service. Therefore, it is generally recommended that the test specimens and mode of loading be chosen to closely simulate the actual components in service (Ritter 1995a, b, Kelly 1999).

### 7.2 Results

#### 7.2.1 Survival rate of test samples after exposure to the artificial mouth

The objective of the artificial mouth test, as already indicated, was to introduce a comparable cycle fatigue component. In the present study all of the samples have been exposed to the artificial mouth to simulate 5 years of service before the fracture
strength test was performed. All the samples survived the exposure to the artificial mouth.

Historically, ceramic inlays and onlays were exposed to the artificial mouth in only two in-vitro studies (Krejci et al. 1993, Mehl et al. 1998). However, for the present study, no comparison data is available in the literature regarding the performance of ceramic inlays and onlays.

**7.2.2 Fracture strength tests after exposure to the artificial mouth**

In the present study all of the samples were loaded until fracture occurred in the universal testing machine after exposure to the artificial mouth. The observed median fracture strength values of the groups were, A (control) 1960 N, B 1567 N, C 1870 N, D 1687 N, E 1705 N and F 1842 N. Data from fracture strength tests of ceramic onlays using natural teeth as abutments after exposure to the artificial mouth are not available in the literature. Despite different preparation and extension designs, the statistical analysis demonstrated no significant differences in the fracture strength values between the test groups and the control group. The fracture strength values of the five groups were comparable to those of natural teeth. All test samples had fracture strength values of more than 800 N. These values exceeded the maximum limit of natural teeth (500 N), as suggested by Kappert (1996). The findings in this study are greater than the fracture strength values of Vitadur N inlays (2680 N) and Ceramco II inlays (1662) luted on natural teeth and unprepared natural teeth (3547 N) as reported by Dietschi et al. (1990). Deviations in the reported fracture forces may be explained by the use of: different types of ceramics, different test methods and different preparation designs. Compared to the study of Dietschi et al. (1990), the testing procedures used in this study were harder, because dynamic loading with thermocycling was performed and tooth mobility was simulated.

The measurement of the fracture strength resulted in an asymmetric distribution of the data. Therefore, instead of the mean, the median was used for the statistical analysis of the fracture resistance data. The small sample size (n = 16), used in the present study, may affect the interpretation of the statistical analysis in this study.
7.2.3 Influence of preparation design on the fracture strength of the ceramic inlays and onlays

In the present study, the statistical analysis showed no significant differences in the fracture strength values between the test groups and the control group (natural teeth). Despite different preparation designs and extensions, the fracture strength of all test specimens in this study reached values that were comparable to those of natural teeth.

The fracture strength of a natural tooth is compromised after tooth preparation or caries as reported by Geurtsen et al. (1989). They examined the fracture strength of 148 extracted human molars after having performed different types of cavity preparations and fillings with various materials (amalgam, direct composite and composite inlays). Unprepared teeth were used as a control group in the study. Results of the fracture tests showed that the prepared-only teeth had the lowest fracture strength value (733 N), while the teeth in the control group had the highest fracture strength value (2088 N). Cotert et al. (2001) compared the cuspal fracture resistance of eighty-four molars restored with five different adhesive materials. The teeth were divided into seven groups. The first five received MOD cavity preparations and were restored with amalgam, composite, composite inlay, cast-metal inlay and ceramic inlay. The sixth and the seventh groups were used as controls. Samples of group 6 were prepared without restoring them. Samples of group 7 were intact teeth and were tested as unprepared. All samples were loaded axially until failure. Results showed that the unprepared teeth had a significantly higher resistance than all other groups, while the prepared-only group was the weakest. In the same study, no significant differences were found in resistance to cuspal fracture among the different restoration groups (Cotert et al. 2001).

It seems in the present study that the different preparation designs of different test groups, along with adhesive cementation, have succeeded in supporting the rest of the tooth structure, have applied an appropriate distribution of stresses generated by the artificial mouth, and enabled the prepared tooth to again reach the fracture strength that it had before preparation. However, no comparison data is available in the literature regarding the effect of preparation design on the fracture strength of
ceramic inlays and onlays placed on natural teeth after exposure to the artificial mouth.

7.2.4 Patterns of fracture of the samples

In the present study, the recorded patterns of fracture of samples of the test groups were typical for ceramic inlays and onlays. Fractures were found mostly in the ceramic material, with the exception of 14 samples (17.5%) where the fracture pattern extended to the tooth structure. This failure of both restoration and tooth can be explained by the fact that the ceramic material (EPC) had almost the same tensile strength values as that of natural teeth. Therefore, when applying the load-to-failure test, both the restoration and the tooth failed. However, it is preferred that the restoration fails alone to preserve the remaining tooth structure (Peters et al. 1993).

The crack initiation for almost all test samples in the present study started at the cement interface to the occlusal aspect of the restoration. This is in agreement with data from Kelly (1999), who reported that crack initiation starts at the cement interface. When a ceramic layer is uniformly supported by, and bonded to, a less stiff material, high tensile stresses develop in the ceramic at its interface with the cement, directly below the loaded area. These interfacial stresses arise from strain differences in the ceramics, cement and dentin because of the ceramic material having a higher modulus of elasticity. Therefore, cracks usually initiate at the interface level, leading to a subsequent total failure of the restoration (Kelly et al. 1990, Kelly 1999). The form of crack initiation and the failure pattern provide strong evidence that the in-vitro test model selected in this study is clinically relevant.
8. Conclusions

Within the limits of this study it can be concluded that:

1. The different preparation designs of ceramic onlays seem to have no influence on the survival rate and fracture strength of these restorations.

2. Clinical data is needed before recommending the EPC material for clinical use.
9. Summary

In this study, the survival rate and fracture strength of ceramic inlays, different types of onlays and unprepared teeth were compared, after exposure to the artificial mouth.

Ninety-six caries-free human upper first molars were used for the experiment. The teeth were randomly divided into five groups of 16 samples each and a control group (A) with no preparation. In group B, inlay preparation was made in a 6° MOD taper box form with rounded and soft internal line angle and 3 mm deep. The isthmus was 3 mm wide. A mesial and distal finishing 1 mm above cemento-enamel junction has been made. In group C, teeth were prepared in the same manner as the first group, then the mesio-palatal cusp was reduced 2 mm with 45° on the occlusal plane and margins were left in an overlapping form. In group D, teeth were prepared in the same manner as the first group, then both palatal cusps were reduced 2 mm with 45° on the horizontal plane. In group E, teeth were prepared in the same manner as the first group, then the palatal and disto-buccal cusps were reduced. In group F, teeth were prepared in the same manner as the first group, then all cusps were reduced. 16 ceramic inlays (group B) and 64 onlays were fabricated using Experimental Press Ceramic material (EPC). The ceramic inlays and onlays were luted to the teeth using Variolink® II. All test and control samples, were loaded in an artificial mouth to simulate 5 years of clinical work (1.2 million chewing cycles). All test samples survived the exposure to the artificial mouth. Then all samples were loaded until fracture occurred in the universal testing machine. The median fracture strength values (in N), were as follows: group B 1567, group C 1870, group D 1687, group E 1705, group F 1842 and group A (control) 1960.

All test groups demonstrated fracture strength values above the maximum suggested load of 500 N. No statistically significant differences in the fracture strength values between the inlay group, the different types of onlay restorations and the natural teeth were recorded. Within the limits of this study, it can be concluded that the different preparation designs of ceramic onlays seem to have no influence on the survival rate and fracture strength of these restorations. However, clinical data is needed before recommending the EPC material for clinical use.
10. Zusammenfassung

11. Appendix

11.1 Results of the fracture strength test (N) after exposure to the artificial mouth

<table>
<thead>
<tr>
<th>Group</th>
<th>Sample</th>
<th>Control</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
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<tbody>
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<td>1</td>
<td>1</td>
<td>2212.26</td>
<td>1592.26</td>
<td>1394.54</td>
<td>1239.46</td>
<td>1929.93</td>
<td>2599.71</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>3328.48</td>
<td>2599.71</td>
<td>1526.70</td>
<td>1782.19</td>
<td>2007.49</td>
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14. Curriculum vitae

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1992 High school certificate by the special test arranged
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Further education: 1998 English language study at the American School,
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