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Juha Pihlaja

TREATMENT OUTCOME OF ZIRCONIA SINGLE CROWNS AND FIXED DENTAL PROSTHESES

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Abstract

Metal ceramic restorations have been used in fixed prosthodontics since the 1950s, but the lack of aesthetics, the inclination to use metal-free materials, possible allergic reactions to metals, and the high cost of high noble alloys have increased the use of all-ceramic materials. The ongoing development of ceramic materials led to the introduction of zirconia to fixed prosthodontics over a decade ago.

The mechanical properties of zirconia have proven to be excellent, but the clinical outcome of conventional fixed zirconia restorations over the long term is unclear. This retrospective clinical study evaluated two- to seven-year outcomes, early complications during prosthetic treatment and short-term failures during the first year of use of zirconia single crowns and fixed dental prostheses (FDPs). The usefulness and durability of zirconia single crowns in abutment teeth of partial removable dental prostheses (RDPs) was also evaluated.

The material consisted of 173 patients treated with zirconia single crowns or FDPs by undergraduate dental students between 2007 and 2010. Of these patients 94 were women and 79 men (mean age 55 years, range 18–79 years). Altogether 268 zirconia single crowns (mean 3 crowns, range 1–12 crowns per patient) had been fabricated for 88 patients and 120 zirconia FDPs (range 3–12 units, mean 4.5 units) for 102 patients. Seventeen patients had received both crown(s) and FDP(s).

The results show that zirconia single crowns and FDPs are a suitable treatment alternative in fixed prosthodontics. Early complications during prosthetic treatment and short-term failures during the first year of use were few. The survival rate of the zirconia single crowns after 3.9 years (2–6 years) was 89% and the success rate was 80%. The survival rate of zirconia FDPs after 4.9 years (3–7 years) was 100% and the success rate was 89%. Zirconia single crowns perform well as abutment teeth of partial RDPs with a metal framework, but fractures in the veneering porcelain remain a problem.

Keywords: ceramic, crown, fixed dental prosthesis, fixed prosthodontics, zirconia

Pihlaja, Juha, Zirkonia-runkoisten kruunujen ja siltojen menestyminen.
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Tiivistelmä

Metallokeraamisia rakenteita on käytetty kiinteässä protetiikassa 1950-luvulta lähtien, mutta puutteet estetiikassa, pyrkimys metallittomiin materiaaleihin, mahdolliset allergiset reaktiot ja jalojen metallien korkea hinta ovat lisänneet kokokeraamisten materiaalien käyttöä. Kokokeraamisten materiaalien kehitystyö on tuonut zirkonian kiinteän protetiikan materiaaliksi.

Zirkonian mekaaniset ominaisuudet ovat osoittautuneet erinomaisiksi, mutta hammaskantoisten kiinteiden zirkonia-runkoisten proteesien kliiniset pitkäaikaistulokset puuttuvat. Tämän retrospektiivisen kliinisen tutkimuksen tarkoituksena oli selvittää zirkonia-runkoisten yksittäisten kruunujen ja zirkonia-runkoisten siltojen menestymistä 2–7 vuoden aikavälillä sekä kartoittaa niiden valmistuksen aikaiset ongelmat ja varhaiset epäonnistumiset ensimmäisen vuoden aikana. Lisäksi tutkittiin zirkonia-runkoisten yksittäisten kruunujen käyttökelpoisuutta ja kestävyyttä metallirunkoisten rankaproteesien tukihampaina.

Materiaali koostui 173 potilaasta, joille hammaslääketieteen opiskelijat olivat tehneet zirkonia-runkoisia yksittäisiä kruunuja tai zirkonia-runkoisia siltoja vuosina 2007–2010. Potilaista 94 oli naisia ja 79 miehiä (keski-ikä 55 vuotta, jakauma 18–79 vuotta). Kaiken kaikkiaan 268 zirkonia-kruunua (keskimäärin 3 kruunua, jakauma 1–12 kruunua potilasta kohti) oli valmistettu 88 potilaalle ja 120 siltaa (keskimäärin 4,5 yksikköä, jakauma 4,5 yksikköä) 102 potilaalle. Seitsemälletoista potilaalle oli tehty sekä kruunuja että siltoja.

Tulokset osoittavat, että zirkonia-runkoiset kruunut ja sillat ovat käyttökelpoisia kiinteässä protetiikassa. Valmistuksenaikaiset ongelmat ja varhaiset epäonnistumiset ovat vähäisiä. Yksittäisten kruunujen selviytymisprosentti 3,9 vuoden jälkeen (2–6 vuotta) oli 89 % ja onnistumisprosentti 80 %. Siltojen selviytymisprosentti 4,9 vuoden jälkeen (3–7 vuotta) oli 100 % ja onnistumisprosentti 89 %. Zirkonia-runkoiset kruunut toimivat hyvin rankojen tukihampaina, mutta niiden ongelmana ovat päällepolttoposliinin lohkeamat.

Asiasanat: hammaskruunu, hammasproteesi, keraaminen, siltaproteesi, zirkonia

The most important things in live aren't things.

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Oulu, April 2016 Juha Pihlaja

Abbreviations

CAD/CAM	computer-aided design/computer-aided manufacturing
CIP	cold isostatic pressing
DCM	direct ceramic machining
FDP	fixed dental prosthesis
FSZ	fully stabilized zirconia
HIP	hot isostatic postcompaction
ISO	International Organization for Standardization
LTD	low temperature degradation, "ageing"
MDP	methacryloxydecyl dihydrogen phosphate
PSZ	partially stabilized zirconia
RDP	removable dental prosthesis
SEM	scanning electron microscope
Y-TZP	yttria-stabilized tetragonal zirconia polycrystals

Original publications

This thesis is based on the following publications, which are referred throughout the text by their Roman numerals:

I Pihlaja J, Näpänkangas R, Raustia A (2014) Early complications and short-term failures of zirconia single crowns and partial fixed dental prostheses. J Prosthet Dent. 112(4):778–783.

II Näpänkangas R, Pihlaja J, Raustia A (2015) Outcome of zirconia single crowns made by predoctoral dental students: a clinical retrospective study after 2 to 6 years of clinical service. J Prosthet Dent. 113(4):289–294.

III Pihlaja J, Näpänkangas R, Kuoppala R, Raustia A (2015) Veneered zirconia crowns as abutment teeth for partial removable dental prostheses: A clinical 4-year retrospective study. J Prosthet Dent. 114(5):633–636.

IV Pihlaja J, Näpänkangas R, Raustia A (2016) Outcome of zirconia partial fixed dental prostheses made by predoctoral dental students: A clinical retrospective study after 3 to 7 years of clinical service. J Prosthet Dent, in press.

Contents

1 Introduction

Since ancient times there has been a need to replace missing teeth. Artificial teeth have been made out of many materials such as human and animal teeth, ivory and wood. An artificial tooth was placed in the socket of a missing tooth or teeth were wired together to be used as a removable denture. The materials were unstable in the oral environment and fabrication methods were primitive. (Ring 1985)

The term conventional fixed prosthodontics refers to restorations, single crowns and fixed dental prostheses (FDPs) that are permanently fixed to the patient's own teeth. First glass inlays and feldspathic porcelain jacket-crowns were fabricated as early as the late 1800s (Kelly *et al.* 1996). Brittleness and poor durability, the main disadvantages of porcelain (Griggs 2007, Miyazaki & Hotta 2011), were a major problem of these early all-ceramic restorations and limited their use. Gold-resin FDPs were the first fixed restorations to replace missing teeth, but with moderate results (Palmqvist & Swartz 1993). Widespread use of all-ceramic materials in fixed prosthodontics is a phenomenon of the last two decades.

A new era in conventional fixed prosthodontics started in the 1950s, when the technique of veneering a strong metal framework with aesthetic porcelain was introduced (O'Brien 2002). These metal ceramic fixed restorations were strong enough to permanently replace missing teeth with adequate aesthetics. Today, metal ceramic restorations are the 'gold standard' of conventional fixed prosthodontics due to their good long-term clinical results (Kelly *et al.* 1996, Tan *et al.* 2004, Näpänkangas & Raustia 2008, Näpänkangas & Raustia 2011). However, moderate aesthetics, inclinations to use metal-free restorations, possible allergic reactions to metals, and the increased cost of high noble alloys have upheld the progress of non-metallic materials (Shenoy & Shenoy 2010, Miyazaki & Hotta 2011, Miyazaki *et al.* 2013). Unfortunately, the brittle nature of ceramics has long limited the use of these more aesthetic materials.

The first dental computer-aided design/computer-aided manufacturing (CAD/CAM) system was introduced in the 1970s (Schepke *et al.* 2015). The development of the new computer-based fabrication system eventually revolutionized the processing of dental restorations (Griggs 2007, Miyazaki & Hotta 2011). The CAD/CAM technique made it possible to mill dental restorations of high-strength ceramic materials that cannot be processed with traditional processing techniques (Miyazaki & Hotta 2011). These materials, especially zirconia, have a wider range of application possibilities than former ceramic materials (Ozkurt & Kazazoğlu 2010, Miyazaki *et al.* 2013). Zirconia has excellent mechanical properties for dental use, but whether it is a durable material for conventional fixed prosthetic restorations over the long term is unclear.

2 Review of literature

2.1 Ceramic materials in fixed prosthodontics

Metal ceramic, ‘porcelain fused to metal', restorations are the ‘gold standard’ of fixed prosthodontics, combining a strong metal framework with an aesthetic porcelain veneer. Despite the good long-term results, the moderate aesthetics and biocompatibility concerns associated with the metals have increased the use of all-ceramic materials. Unfortunately, brittleness and poor durability have long limited the use of all-ceramic restorations. (Heintze & Rousson 2010, Miyazaki & Hotta 2011, Miyazaki *et al.* 2013)

The first all-ceramic feldspathic porcelain jacket-crowns were fabricated in the late 1800s, but advancements in all-ceramic materials took place as late as in the early 1980s, when shrink-free alumina crowns (Cerestone®, Johnson & Johnson) and castable, mica-reinforced, glass-ceramic crowns (Dicor®, Corning) were introduced (Kelly *et al.* 1996, Kelly & Benetti 2011 Li *et al.* 2014). In the early 1990s, ceramic materials evolved as leucite-reinforced glass ceramics (IPS Empress®; Ivoclar Vivadent) and glass-infiltrated alumina ceramics (InCeram®; Vita Zahnfabrik) were introduced (Kelly & Benetti 2011). Leucite-reinforced glass-ceramic crowns had similar strength and toughness values as mica-reinforced, but were stronger, possibly due to a strong micromechanical bond after etching and priming (Kelly 2004). Glass-infiltrated alumina ceramics were much stronger than former all-ceramic materials, but the translucency of the material was poor (Shenoy & Shenoy 2010). In 1998 a lithium disilicate-reinforced glass-ceramic material (IPS Empress II®) was introduced by Ivoclar Vivadent (Pieger *et al.* 2014). During the last two decades, all ceramic systems have evolved significantly.

Traditional techniques for processing all-ceramic materials include layering (powder condensation), hot-pressing and slip-casting (Griggs 2007). The conventional layering technique is technically sensitive and is usually used to apply veneering porcelain on high-strength frameworks, as porosity and relatively low strength limit the indications (Griggs 2007). Slip-casting is a complicated method used to fabricate infiltrated alumina ceramics whereas hot-pressing is used with pressable glass-ceramics to press liquid glass into a mould (Griggs 2007). A hot-pressing, press-on-metal (PoM) technique can also be used with metal ceramic restorations as an alternative to the technique-sensitive and time-consuming porcelain layering technique (Khmaj *et al.* 2014, Lee 2016).

The first dental computer-aided design/computer-aided manufacturing (CAD/CAM) system was introduced in the 1970s and the first CAD/CAM-fabricated all-ceramic restoration was fabricated from feldspathic ceramic in 1983 (Li *et al.* 2014, Schepke *et al.* 2015). Dental CAD/CAM systems consist of three main phases: scanning the teeth intraorally or from a cast, designing the restoration by computer and fabricating the restoration with a milling machine (Miyazaki & Hotta 2011). The development of computer-based systems revolutionized the processing techniques of dental restorations and the use of ceramic materials (Griggs 2007, Miyazaki & Hotta 2011). With CAD/CAM systems it is possible to design and mill dental restorations chairside. The development of CAD/CAM systems made it possible to mill the frameworks of the restorations from high-strength polycrystalline ceramics like densely sintered alumina and zirconia (Griggs 2007). Subtractive manufacturing with computer-aided machining is the state-of-the-art fabrication method at the moment, but in the future, additive manufacturing with 3D printing technologies are coming to dentistry (van Noort 2012, Stansbury & Idacavage 2015).

Nowadays, most ceramic restorations are milled from pre-fabricated blocks. There are three different concepts of restoration design for full-contour ceramic restorations. Ceramic restorations can be either fabricated from a single material as a monolithic restoration or stronger ceramic can serve as a framework that is thoroughly veneered with a more aesthetic porcelain layer (Miyazaki *et al.* 2013, Moscovitch 2015). The third way is a so-called hybrid restoration, in which the veneering layer is used only where aesthetically needed (Moscovitch 2015).

2.2 Classification of all-ceramic materials

All-ceramic materials are divided into four sub-categories according to the microstructure of the material: glass-ceramics (predominantly glass), glass-ceramics with fillers, crystalline ceramics with glass fillers and polycrystalline ceramics (Shenoy & Shenoy 2010). Highly aesthetic materials are mainly glass, and a higher crystalline content strengthens the material, but weakens transparency (Kelly 2004). The use of crystalline ceramics with glass fillers has decreased due to increased use of lithium disilicate-reinforced glass-ceramics and (zirconia-based) polycrystalline ceramics (Gracis *et al.* 2015). Lately, a new classification system that divides all ceramic materials into glass-matrix ceramics, polycrystalline ceramics and resin-matrix ceramics, has been proposed (Gracis *et al.* 2015).

2.2.1 Glass-ceramics

Glass-ceramics consist mainly of silica and alumina (Shenoy & Shenoy 2010). The optical properties of mainly silica-based ceramics are excellent, but the brittle nature and low fracture toughness of the material have limited its use (Griggs 2007, Miyazaki & Hotta 2011). Adding reinforcing fillers like leucite and especially lithium disilicate to the glass matrix strengthens the material while preserving its good optical properties (Shenoy & Shenoy 2010). When lithium disilicate is added, flexural strength and fracture toughness are over three times higher than with leucite (Shenoy & Shenoy 2010).

With silica-based ceramics, pretreatment before adhesive cementation includes surface roughening with hydrofluoric acid etching and surface activation with silanization, leading to substantially improved chemical bonding (Blatz *et al.* 2003, Özcan & Vallittu 2003). Advancements in all-ceramic materials and in fabrication and bonding procedures have led to the introduction of mini-invasive techniques and monolithic restorations to fixed prosthodontics (Magne *et al.* 2015, Sulaiman *et al.* 2015b, Sailer *et al.* 2015). A minimal intervention concept is the principal approach in modern dentistry (Dalli *et al.* 2012), but conventionally fixed restorations have required significant tooth structure removal because of material properties and retention (Magne *et al.* 2015). Monolithic, tightly bonded lithium disilicate restorations have held up well in single crown applications, but are not suitable for posterior FDPs (Pieger *et al.* 2014).

2.2.2 Alumina- and zirconia-based polycrystalline ceramics

Alumina- and zirconia-based polycrystalline ceramics do not have a glassy matrix (Kelly 2004). These densely sintered materials are tougher and stronger than other all-ceramic materials (Shenoy & Shenoy 2010). Unfortunately, due to their high crystalline content, they are less translucent than other all-ceramic materials such as glass-infiltrated ceramics, and are therefore veneered with porcelain for better aesthetics (Kelly 2004). These veneered, bi-layered systems have strong cores that are characterized by a porcelain layer.

A relatively high incidence of core fractures due to the high elastic modulus of alumina, in addition to the better mechanical properties of zirconia, has decreased the use of alumina (Gracis *et al.* 2015). Zirconia has become popular because a milled zirconia core is strong enough to serve as the framework of posterior FDPs (Manicone *et al.* 2007). Lately, improvements in the translucency of zirconia have led to development of high-strength monolithic zirconia systems (Denry & Kelly 2014). Monolithic zirconia is more fracture resistant than monolithic lithium disilicate, but is not yet comparable in aesthetics (Zhang *et al.* 2013). Its opacity still limits its use mostly to areas outside of the aesthetic zone (Sulaiman *et al.* 2015b). With non-silica-based polycrystalline ceramics, hydrofluoric acid etching is ineffective and adhesive bonding is challenging (Blatz *et al.* 2003, Özcan & Vallittu 2003). Adhesive cementation of polycrystalline ceramics would decrease the need for excessive tooth preparation.

2.3 Physical properties of zirconia

Zirconium is a strong grey-white transition metal that was found in 1798 (Piconi & Maccauro 1999). Zirconium is not found as a pure metal in nature, because zirconium reacts with oxygen (zirconium dioxide, ZrO_2, "zirconia") and/or silica (zirconium silicate, $ZrSiO_4$) (Lughi & Sergo 2010). Zirconium silicate—zircon—is a silicate mineral that has been known as a gemstone since biblical times (Piconi & Maccauro 1999).

Zirconia is a dioxide of zirconium (Manicone *et al.* 2007). The organization of crystals in zirconia is dependent on temperature: monoclinic (M) at room temperature, tetragonal (T) between 1170-2370°C and cubic (C) at higher temperatures (Piconi & Maccauro 1999). Pure zirconia is monoclinic at room temperature but its cubic and tetragonal phases can be stabilized at room temperature by adding metallic oxides such as calcium oxide (CaO), magnesium oxide (MgO), lanthanum oxide (La_2O_3), cerium oxide (CeO_2), or yttrium oxide (Y_2O_3) (Kelly & Denry 2008, Li *et al.* 2014).

Stabilizing zirconia with yttrium oxide enhances its mechanical properties more than with other oxides (Manicone *et al.* 2007). Zirconia can also be stabilized by cerium oxide (ceria), but dispersion of alumina is needed to increase the flexural strength of the material (Miyazaki *et al.* 2013, Tanaka *et al.* 2015). Ceria- stabilized zirconia/alumina nanocomposite has very good mechanical properties but more clinical studies will be needed (Miyazaki *et al.* 2013, Tanaka *et al.* 2015). Zirconia can be stabilized partially by 2-5 mol-% of yttrium oxide (partially stabilized zirconia, PSZ), or fully by 8 mol-% of yttrium oxide (fully stabilized zirconia, FSZ) (Kelly & Denry 2008). Dental zirconia, usually referred to as yttria-stabilized tetragonal zirconia polycrystals (Y-TZP), is commonly partially stabilized (Gracis *et al.* 2015). Fully stabilized zirconia is more translucent than partially stabilized zirconia (Sulaiman *et al.* 2015b).

The favourable mechanical and chemical properties of zirconia, like strength, toughness, resistance to corrosion and wear, good chemical and dimensional stability, and biocompatibility have allowed zirconia to be used in high-strength parts like blades and valves (Piconi & Maccauro 1999). Zirconia's flexural strength from 900 to 1200 MPa and fracture toughness of 9–10 $MPam^{1/2}$ (Christel *et al.* 1989) are higher than those of any other dental all-ceramic material. The mechanical properties of the most common ceramic materials in fixed prosthodontics are shown in Table 1. Zirconia (210 GPa) and stainless steel (193 GPa) have a similar Young's modulus, which measures the force needed to compress or stretch a certain material (Ozkurt & Kazazoğlu 2010).

One of the main advantages of zirconia is its ability to resist crack propagation through a phenomenon called transformation toughening. External stress to zirconia induces a local transformation from metastable tetragonal zirconia to stable monoclinic zirconia; its volume expands and the crack is shielded (Lughi & Sergo 2010). On the other hand, in a moist environment, this metastability of the tetragonal phase may cause a spontaneous transformation from the metastable tetragonal phase to the stable monoclinic phase, decreasing the strength of the material (Chevalier 2006). This phenomenon is called low-temperature degradation (LTD, "ageing"). The main factors of LTD are the content of the stabilizer, grain size and residual stress (Lughi & Sergo 2010). Increased sintering temperature and time possibly increases the amount of LTD by enlarging grain size and lowering the content of the stabilizer (Inokoshi *et al.* 2014b). LTD can be prevented or decreased by following ISO engineering guidelines (Lughi & Sergo 2010), and colouring the zirconia increases its resistance to LTD (Nakamura *et al.* 2016).

Table 1. Mechanical properties of the most used ceramic materials in fixed prosthodontics.

Ceramic system	(Reinforcing) material	Brand (manufacturer)	Flexural strength[1]	Fracture toughness[2]	Reference
1) glass-ceramics	Feldspathic porcelain	-	100	1.0	Miyazaki & Hotta (2011)
2) glass-ceramics with fillers	Leucite	IPS Empress (Ivoclar Vivadent)	160	1.5-1.7	Raigrodski 2004, Li *et al.* 2014
	Lithium disilicate	IPS e.max (Ivoclar Vivadent)	300-400	2.8-3.5	Raigrodski 2004
3) crystalline ceramics with glass fillers	Glass-infiltrated alumina	In-Ceram Alumina (VITA Zahnfabrik)	236-600	3.1-4.6	Raigrodski 2004
	glass-infiltrated zirconia toughened alumina	In-Ceram Zirconia (VITA Zahnfabrik)	421-800	6-8	Raigrodski 2004
4) polycrystalline ceramics	densely sintered alumina	Procera AllCeram (Nobel Biocare)	487-699	4.48-5.6	Raigrodski 2004
	Yttria Stabilized Zirconia	Cercon (Dentsply), Lava (3M ESPE), Procera (Nobel Biocare), Prettau Zirconia (Zirkonzahn), Zirconia (Zirkonzahn), BruxZir (Glidewell Lab.)	900-1200	9-10	Raigrodski 2004

[1]MPa, [2]MPa/m$^{1/2}$

2.4 Zirconia in dentistry

Zirconia's favourable mechanical and chemical properties have also allowed it to be used as a biomaterial (Piconi & Maccauro 1999). It was first introduced for biomedical purposes in orthopaedics in the 1960s, to be used in hip prostheses (Piconi & Maccauro 1999). Zirconia was introduced for dental purposes in the early 1990s (Raigrodski 2004). Zirconia's biocompatibility has been proved both *in vitro* and *in vivo*; zirconia is non-cytotoxic, non-mutagenic and no local or systemic adverse reactions have been identified (Piconi & Maccauro 1999, Manicone *et al.* 2007). Zirconia has good chemical stability, but alterations of zirconia's surface to some extent are seen in an acidic environment (Sulaiman *et al.* 2015c).

In prosthodontics zirconia has a wider range of possible applications than other all-ceramics (Özkurt & Kazazoğlu 2010). It has been used as a framework material for single crowns, FDPs, inlay-retained FDPs and resin-bonded FDPs (Al-Amleh *et al.* 2010, Kern 2015). These restorations can also be fabricated as monolithic restorations without veneering porcelain (Moscovitch 2015, Sulaiman *et al.* 2015b). Zirconia is also used as a reinforcing material of other materials such as zirconia-containing lithium silicate (Denry & Kelly 2014) and glass-infiltrated alumina (Shenoy & Shenoy 2010).

Implant abutments have also been made of zirconia. Titanium abutments are very durable, but their grey colour impairs aesthetics. Zirconia implant abutments enhance the aesthetics of the restoration, minimize the gray colour of the implant in the marginal mucosa, decrease bacterial adhesion and have soft tissue integration similar to titanium (Sailer *et al.* 2009b). Experiments with zirconia implants have also been conducted. Osseointegration, biocompatibility, and the health of soft tissues around zirconia implants have turned out to be excellent, but long-term studies are needed (Özkurt & Kazazoğlu 2010, Apratim *et al.* 2015). In endodontics zirconia has been used as a post material and in orthodontics zirconia is used for fabrication of orthodontic brackets with varying results (Özkurt & Kazazoğlu 2010).

2.5 Processing techniques of zirconia restorations

Zirconia restorations can only be fabricated by milling from pre-fabricated blocks (Gracis *et al.* 2015). Zirconia blocks are fabricated from ZrO_2 powder containing stabilizing yttrium (Oh *et al.* 2010) (Fig. 1.) The blocks are packed by cold isostatic pressing (CIP) to 70% of their theoretical maximum density (Denry & Kelly 2008, Oh *et al.* 2010, Shenoy & Shenoy 2010). This green-stage zirconia can then be partially sintered at high temperature and fully sintered by hot isostatic pressing (HIP) at higher temperature and under high pressure (Oh *et al.* 2010 Nakamura *et al.* 2016).

The framework of a zirconia restoration can be designed by CAD or by a conventional waxing technique and then digitally scanned and fabricated by CAM (Raigrodski 2004), but the CAD/CAM technique is more accurate than CAM from a waxed mould (Abduo *et al.* 2010). Zirconia restorations can be hard machined from fully sintered blocks or soft machined from green-stage or partially sintered blocks (Miyazaki *et al.* 2013). Milling the zirconia restorations and/or frameworks from partially sintered blocks saves time and milling machinery, because pre-sintered zirconia is easier to mill (Miyazaki *et al.* 2013). The restoration is designed by CAD software that enlarges the restoration by 20-25%, because final sintering after milling causes volume shrinkage (Raigrodski 2004). Another way to mill zirconia restorations is hard machining from fully-sintered blocks. Hard machining requires robust milling equipment and is more time consuming, but no firing is needed after milling (Denry & Kelly 2008, Miyazaki *et al.* 2013).

The final procedure after milling is aesthetic characterization of the framework. When translucent monolithic zirconia is used, the restoration is characterized by polishing, staining, and glazing (Kim *et al.* 2013, Kim & Kim 2014, Moscovitch 2015, Sulaiman *et al*. 2015b). Traditionally, the framework is characterized by feldspathic porcelain veneer using the powder condensation technique; moist porcelain powder is used to build up the veneering layer and the fluxing agent is then removed by firing (Griggs 2007). This veneering layer can be full-contour and cover the whole restoration or it can be placed only where aesthetically needed (Moscovitch 2015).

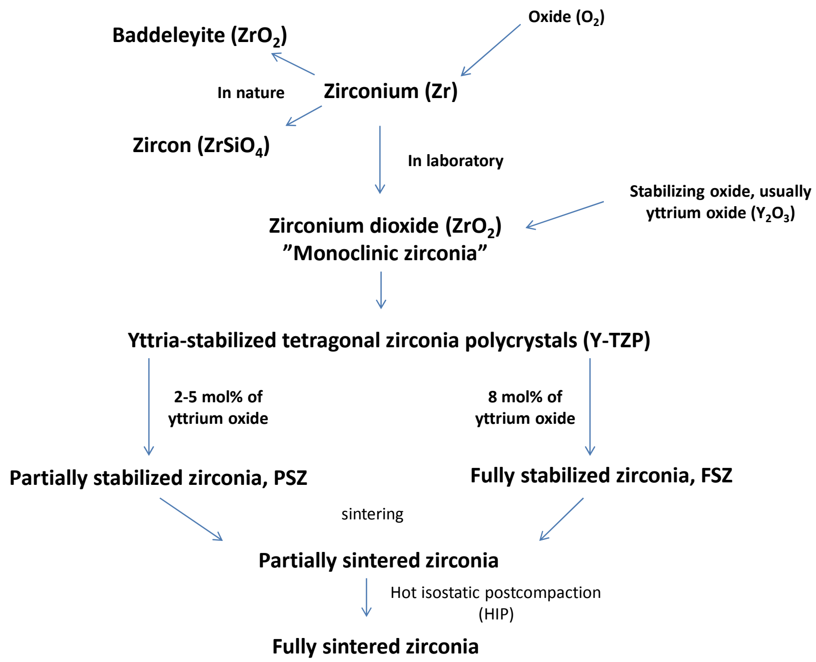

Fig. 1. Zirconium is not found as a pure metal in nature, because zirconium reacts with oxygen. The tetragonal phase of zirconia can be stabilized at room temperature by adding metallic oxides such as yttrium oxide (Y_2O_3). Zirconia can be partially or fully stabilized. Zirconia blocks can be milled in a partially or fully sintered state.

2.6 Terminology

Zirconia has been in the dental market for two decades and numerous materials and processing techniques are available. The widespread of material in the field has confused the nomenclature and terminology of zirconia materials and processing techniques. Accurate recording of treatment materials into patient records is essential, but generally accepted accurate terminology is important also in communication between professionals.

The first confusing term is related to the design of the restoration. The restoration can be milled from a block of single material as a monolithic restoration (Ramos *et al.* 2015, Reich 2015). This monolithic restoration is sometimes referred to as full-contour restoration (Reich 2015). These terms have a difference; the term full contour refers to the design—full- or partial-contour—

of the restoration (Marchack *et al.* 2011), whereas the term monolithic refers to a single material being used. Another way to design zirconia restoration is to mill a strong framework from zirconia and veneer it with a more aesthetic porcelain layer. These restorations have been referred to in literature as zirconia-based, veneered or bi-layered restorations. The veneering layer can also be placed only where aesthetically needed; these are called hybrid or minimally veneered restorations (Moscovitch 2015, Ramos *et al.* 2015).

Another confusing term is related to the fabrication process. Zirconia can be partially or fully stabilized referring to the process of stabilizing the tetragonal or cubic phase of zirconia at room temperature (Kelly & Denry 2008). Zirconia restorations can also be fabricated as partially-sintered (soft machining) or fully-sintered (hard machining) (Denry & Kelly 2008). Stabilizing is done before the fabrication of the block, whereas sintering is done after the block has been fabricated.

2.7 Problems related to veneered zirconia restorations

Because of its excellent technical and biological properties, zirconia has become very popular and widely used in fixed prosthodontics. There are, however, a few minor and major clinical problems related to zirconia restorations. Common problems related to zirconia restorations, defined in meta-analyses and reviews, are secondary caries, marginal discolouration, ceramic fractures, chipping of the veneering porcelain and loss of retention (Raidrodski *et al.* 2012, Larsson & Wennerberg 2014, Pjetursson *et al.* 2015, Sailer *et al.* 2015). In addition, possible abrasiveness of zirconia restorations to antagonist teeth due to the hardness of zirconia has raised concerns in dentistry (Oh *et al.* 2002, Miyazaki *et al.* 2013, Sripetchdanond & Leevailoj 2014).

2.7.1 Secondary caries

Oral pathogenic biofilm is the primary etiologic factor of caries and periodontitis (Sbordone & Bortolaia 2003, Filoche *et al.* 2010, Bremer *et al.* 2011). Low bacterial adhesion of the restoration is a crucial factor in the longevity of the restoration (Bremer *et al.* 2011). Important factors affecting plaque adhesion to the restoration are surface roughness of the material used and marginal fit and contour of the restoration (Becker & Kaldahl 2005, Busscher *et al.* 2010, Contrepois *et al.* 2013) Less bacterial adhesion has been found on smooth surfaces than on rough ones (Busscher *et al.* 2010), and bacterial adhesion to ceramic materials has been noted to be low due to their surface characteristics (Wang *et al.* 2014). Zirconia has been shown to exhibit bacterial adhesion similar to titanium (Lima *et al.* 2008) and lower than glass-ceramics and other dental restorative materials (Bremer *et al.* 2011). On metals like gold and amalgam, the biofilm is thick but barely viable, whereas on ceramics the biofilm is thin but highly viable (Busscher *et al.* 2010). The low viability of the biofilm on metals is possibly related to toxic releases and/or hampered supply of nutrients to a thick biofilm (Busscher *et al.* 2010). *In vitro* studies have shown that the marginal gap of zirconia restorations is equal to that of metal ceramic restorations (Biscaro *et al.* 2013, Song *et al.* 2013). The size of the marginal gap is dependent on the CAD/CAM system and the different zirconia materials, but is always clinically acceptable (Biscaro *et al.* 2013, Brawek *et al.* 2013, Contrepois *et al.* 2013, Song *et al.* 2013). A high incidence of secondary caries and marginal discolouration in some earlier studies concerning zirconia restorations is believed to be related to the insufficient marginal fit of these restorations due to early-stage prototype CAM systems (Roediger *et al.* 2010, Sax *et al.* 2011, Rinke *et al.* 2013b).

2.7.2 Chipping of veneering ceramics

Clinical studies have shown a relatively high incidence of chipping of the veneering porcelain of zirconia restorations (Al-Amleh *et al.* 2010, Raigrodski *et al.* 2012a, Sailer *et al.* 2015, Pjetursson *et al.* 2015). A meta-analysis by Sailer *et al.* (2015) estimated that the cumulative chipping rate after five years was 3.1% for zirconia single crowns and 2.6% for metal ceramic single crowns. In a meta-analysis, Pjetursson *et al.* (2015) reported that the cumulative chipping/fracture rate after five years was 14.5% for zirconia FDPs and 5.0% for metal ceramic FDPs.

Several possible factors have been suggested to affect the survival of veneering ceramics on zirconia restorations. Material related factors such as a mismatch in thermal expansion coefficients between the veneer and zirconia (Fischer *et al.* 2009, Swain 2009), surface characteristics of zirconia weakening the bond to the veneer (Aboushelib *et al.* 2006) and microtensile bond strength of different veneering ceramics (Aboushelib *et al.* 2006) have been studied. Others have investigated technique-related aspects such as the anatomical design of the framework supporting the veneering porcelain (Rosentritt *et al.* 2009, Guess *et al.* 2013, Preis *et al.* 2013), different thicknesses of veneering porcelain (Benetti *et* *al.* 2014, Paula *et al.* 2015), slow cooling and heating procedures during firing (Tan *et al.* 2012, Preis *et al.* 2013, Benetti *et al.* 2014, Paula *et al.* 2015), or changing the layering technique of porcelain from veneered to pressed porcelain (Preis *et al.* 2013) or to lithium disilicate (Seydler & Schmitter 2015). It seems that the anatomical design of the core (Rosentritt *et al.* 2009, Preis *et al.* 2013) and a slow cooling protocol (Benetti *et al.* 2014, Denry & Kelly 2014, Paula *et al.* 2015) are the most important factors that lower the incidence of chipping.

2.7.3 Wear of the antagonist tooth

Veneering porcelain is reported to be more abrasive than natural enamel or zirconia (Kim *et al.* 2012, Burgess *et al.* 2014, Lawson *et al.* 2014). Clinical follow-up studies have revealed a high incidence of occlusal surface roughness in the veneering porcelain of zirconia restorations, and it was suspected to be related to chipping of the veneering porcelain later (Molin & Karlsson 2008, Sailer *et al.* 2009a, Schmitt *et al.* 2011, Koenig *et al.* 2013). The surface roughness of a ceramic restoration seems to increase enamel wear on the antagonist tooth (Ghazal & Kern 2009).

In vitro studies have shown that enamel wear in teeth opposing monolithic zirconia is less or equivalent to enamel-enamel wear (Janyavula *et al.* 2013, Burgess *et al.* 2014, Kim *et al.* 2012). In a recent clinical study it was noted that polished monolithic zirconia crowns caused less wear than conventional glazed metal ceramic crowns but more than natural enamel (Mundhe *et al.* 2015). Polished zirconia seems to be more wear-friendly than glazed zirconia (Janyavula *et al.* 2013, Stawarczyk *et al.* 2013, Passos *et al.* 2014). The initial roughness and friction coefficient of polished zirconia seem to be lower than those of glazed zirconia (Heintze *et al.* 2008, Janyavula *et al.* 2013) and the glaze is worn away over time, possibly acting as a third-body abrasive (Heintze *et al.* 2008, Janyavula *et al.* 2013). If ceramic material is not polished prior to glazing, the roughness of the restoration will increase further after the glaze has worn away and the underlying unfinished surface becomes exposed (Heintze *et al.* 2008). In a review concerning factors affecting enamel and ceramic wear, Oh *et al.* (2002) concluded that there is no strong correlation between the hardness of ceramic material and wear of opposing tooth, whereas the ceramic microstructure and roughness of the contact point surface are related to increased enamel wear. On the other hand, Stawarczyk *et al.* (2013) reported a low incidence of wear but high incidence of enamel cracks in the antagonist teeth of monolithic zirconia restorations.

2.7.4 Loss of retention and adhesive bonding

The rate of loss of retention of zirconia crowns seems to be significantly higher than with metal ceramic crowns, the rate being 4.5% for zirconia and 0.6% for metal ceramic single crowns (Sailer *et al.* 2015). In a meta-analysis of FDPs the findings are similar; zirconia FDPs had a five-year loss of retention rate of 6.2%, whereas the loss of retention rate for metal ceramic FDPs was 2.1% (Pjetursson *et al.* 2015).

Adhesive chemical bonding and micro-mechanical interlocking are needed for a strong resin bond (Thompson *et al.* 2011). With silica-based ceramics, surface pre-treatment includes surface roughening and cleansing with hydrofluoric acid (Blatz *et al.* 2003), but with zirconia the hydrofluoric acid is ineffective (Yang *et al.* 2007, Yang *et al.* 2008) and other roughening techniques are needed (Thompson *et al.* 2011). There is no universal pre-treatment protocol for bonding zirconia, but several studies have shown that cleaning and roughening the surface by airborne particle abrasion with Al_2O_3 particles increases bond strength (Wolfart *et al.* 2007, Phark *et al.* 2009, Amaral *et al.* 2014, Yi *et al.* 2015). Other pre-treatment protocols like tribochemical silicacoating (Bottino *et al.* 2005, Atsu *et al.* 2006, Papia *et al.* 2014) and selective infiltration etching (Aboushelib *et al.* 2010) have also been investigated. Selective infiltration etching is a promising pre-treatment method, but is a time-consuming and technically sensitive procedure (Melo *et al.* 2015). Wolfart *et al.* (2007) have suggested that air-abrasion increases bond strength by cleansing the surface from try-in contamination, increases the surface area, and chemically activates the surface. Other cleansing methods such as water rinsing, alcohol cleaning or phosphoric acid are ineffective when compared with airborne-particle abrasion, and they leave a thin layer of saliva and other contamination to zirconia surface after try-in (Yang *et al.* 2007, Yang *et al.* 2008). The increase in air pressure may cause fractures and yet does not seem to increase long-term bond strength (Wolfart *et al.* 2007).

Reviews regarding *in vitro* studies of zirconia bonding have shown that air-abrasion in combination with a cement or primer containing methacryloxydecyl dihydrogen phosphate (MDP) can achieve a durable bond to zirconia (Inokoshi *et al.* 2014a, Papia *et al.* 2014, Kern 2015). This has been noted also in clinical studies. According to the review it was recommended to use moderate-pressure air-abrasion in combination with a phosphate monomer-containing primer or a luting resin to durably bond to zirconia and other oxide ceramics (Kern 2015).

The thickness of the zirconia restoration or framework and the brand of zirconia and resin cement have an effect on the time and energy needed for monomer conversion of dual-polymerizing resin cement (Sulaiman *et al.* 2015a). Adhesive chemical bonding does not reduce the importance of retentive abutment preparation (Podhorsky 2015).

2.8 Survival of zirconia restorations

The definition of complications and failures has varied greatly, causing difficulty in comparing failure, survival and especially success rates of fixed restorations (Tan *et al.* 2004, Anusavice 2012). In a review by Tan *et al.* (2004), complications were divided into biological and technical categories. Biological complications included secondary caries, loss of pulp vitality and progression of periodontal disease whereas technical complications included loss of retention, abutment tooth fractures and material fractures (veneer or framework) (Tan *et al.* 2004).

Follow-up studies concerning zirconia restorations are shown in Table 2. A few review articles and meta-analyses, however, have summarized the clinical success and survival of zirconia restorations. A meta-analysis by Sailer *et al.* (2015) estimated a survival rate of 91.2% for zirconia single crowns and 95.7% for metal ceramic single crowns after five years. Larsson & Wennerberg (2014) estimated five-year cumulative survival rate of 95.9% for zirconia single crowns. A meta-analysis by Pjetursson *et al.* (2015) estimated a five-year survival rate of 90.4% for zirconia FDPs and 94.4% for metal ceramic FDPs.

Table 2. Follow-up studies concerning zirconia restorations.

Restoration type	Authors	No. of patients	No. of restorations	Mean follow-up time (years)	No. of failures	Survival (%)
Single crowns	Beuer *et al.* (2010)	38[1]	50	2.9	0	100
	Schmitt *et al.* (2010)	10	19	3.3	0	100
	Sagirkaya *et al.* (2012)	42	74	4.0	4	96
	Örtorp *et al.* (2012)	162	205	5.0	19	91
	Monaco *et al.* (2013)	398	1132	5.0	21	98
	Passia *et al.* (2013)	123	123	6.0	31	73
	Rinke et al. (2013b)	49[1]	53	3.0	2	95
	Nejatidanesh *et al.* (2016)	139	324	5.1	6	98
	Rinke *et al.* (2016)	45[1]	50	5.3	3	94
	Tartaglia *et al.* 2015	88[1]	130	7.0	9	93
FDPs	Edelhoff *et al.* (2008)	17	21	3.3	0	100
	Molin & Karlsson (2008)	18	19	5.0	0	100
	Tinschert *et al.* (2008)	46	65	3.0	0	100
	Beuer *et al.* (2009)	19	21	3.3	2	91
	Sailer *et al.* (2009)	53[1]	36	3.4	0	100
	Wolfart *et al.* (2009)	21	24	4.0	1	96
	Roediger *et al.* (2010)	75	99	4.0	7	94
	Sax *et al.* (2011)	21	26	10.7	15	67
	Schmitt *et al.* (2011)	15	15	4.0	0	100
	Lops *et al.* (2012)	24	24	6.5	2	89
	Pelaez *et al.* (2012)	37[1]	20	4.2	1	95
	Raigrodski *et al.* (2012b)	16	20	5.0	0	90
	Sagirkaya *et al.* (2012)	28	n/a	4.0	1	99
	Schmitter *et al.* (2012)	19	22	5.0	5	82
	Sorrentino *et al.* (2012)	37	48	5.0	0	100
	Rinke *et al.* (2013a)	75	99	7.0	19	83
	Håff *et al.* (2015)	30	33	9.6	2	94
	Solá-Ruíz *et al.* (2015)	27	27	7.0	3	89
	Tartaglia *et al.* 2015	88[1]	49	7.0	0	100

[1]Total number of patients in the study.

3 Aims of the study

Zirconia has excellent mechanical and biological properties, but whether it is a durable material for conventional fixed prosthetic restorations is unclear. These properties could also make zirconia a useful material for abutment teeth of partial removable dental prostheses (RDPs), but no clinical studies were available. The hypothesis was that zirconia crowns, FDPs and abutment teeth of RDPs would experience few early and short-term complications and would perform well in both anterior and posterior regions in dentition, although more complications can be expected with increasing time of function.

The specific aims were

1. to evaluate the incidence of early complications during prosthetic treatment and short-term failures during the first year of use of zirconia single crowns and fixed dental prostheses (FDPs)
2. to evaluate the success and survival of zirconia single crowns after two to six years of clinical service
3. to evaluate the outcome of short- and long-span zirconia FDPs after three to seven years of clinical service
4. to evaluate the usefulness of zirconia single crowns in abutment teeth of partial removable dental prostheses (RDPs)

4 Material and methods

4.1 Description of the material

The prosthetic treatment and the clinical examinations were conducted at the Dental Training Clinic, Oral Health Services, City of Oulu, and at the Institute of Dentistry, University of Oulu, Finland. The study design was approved by the Ethical Committee of the Northern Ostrobothnia Hospital District (100/2013).

Patient records (Effica; Tieto, Finland) were searched for patients treated with zirconia restorations by predoctoral dental students between 2007 and 2010. Anamnestic and clinical information related to prosthetic treatment was recorded from patient records. Any dental treatment after the prosthetic treatment in Oral Health Services, City of Oulu, was obtained from the patient records.

4.2 Study population

The material consisted of 173 patients treated with zirconia single crowns and/or zirconia fixed dental prostheses (FDPs)(Fig. 2). Of these patients 94 were women and 79 men (mean age 55 years, range 18–79 years). Altogether 268 zirconia single crowns (mean 3 crowns per patient, range 1–12 crowns) were fabricated for 88 patients and 120 zirconia FDPs (range 3–12 units, mean 4.5 units, 342 abutments and 190 pontics) for 102 patients. Seventeen patients had received both crown(s) and FDP(s).

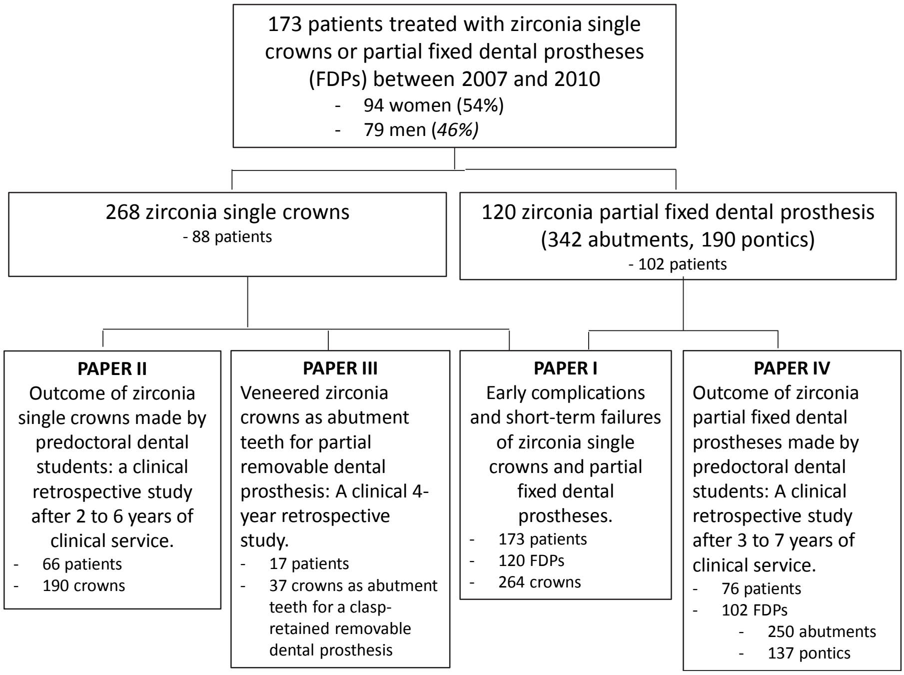

Fig. 2. Flow chart of the study material.

4.3 Materials of the restorations

The materials of the zirconia frameworks used were Zirkonzahn Zirconia (Zirkonzahn, Germany), NobelProcera Zirconia (Nobel Biocare, Switzerland), and Prettau Zirconia (Zirkonzahn, Germany). The frameworks of Zirkonzahn Zirconia and Prettau Zirconia were fabricated by manual milling whereas the frameworks of NobelProcera Zirconia were fabricated with CAD/CAM manufacturing.

For Zirkonzahn Zirconia and Prettau Zirconia, the connector's cross-sectional area requirement was 9.0 mm^2 and the minimal thickness of the frameworks 0.4 mm. For NobelProcera Zirconia, the connector's cross-sectional area requirement was 6.0mm^2 (the anterior area) and 9.4 mm^2 (the posterior area) and the minimal thickness was 0.6 mm. Prettau Zirconia was monolithic whereas on Zirkonzahn

Zirconia (GC Initial Zr; GC Europe) and Nobel Procera Zirconia (VITA VM 9; VITA Zahnfabrik) the veneering porcelain was hand-layered.

4.4 Clinical procedures during prosthetic treatment

Treatments were performed by predoctoral dental students and supervised by prosthodontists. All the patients had received pre-prosthetic treatments before prosthetic treatment including cariological, periodontal, and endodontic treatment, if needed.

Composite resin (Filtek Z250; 3M Deutschland GmbH, Germany) was used to restore the abutment when needed and endodontically treated teeth were reinforced with a fiber post (RelyX Fiber post; 3M Deutschland GmbH, Germany). Preparations guidelines by Shillingburg *et al.* (2012) were followed during prosthetic treatment for both single crowns and abutment teeth of FDPs: heavy chamfer finish line preparation with total wall convergence of six degrees, 1.5 mm axial clearance, 2 mm anatomically adequate occlusal reduction and a functional cusp bevel to ensure sufficient material thickness. In preparation of abutment teeth for zirconia single crowns that serve as an abutment tooth for a RDP with a metal framework, the extra space needed for occlusal rest seats and guide planes were taken into account. The RDPs were fabricated according to Scandinavian guidelines (Molin Thoren & Gunne 2012). If a zirconia single crown was prepared to serve as an abutment tooth for a RDP with a metal framework, the rest seat of the RDP was left with a zirconia surface and veneering porcelain was placed only where needed for aesthetic reasons. The metal frameworks of the RDPs were fabricated from a cobalt-chromium alloy and the denture bases were made of acrylic resin.

Prior to cementation, the restorations were airborne-particle abraded with aluminum oxide (110 µm, 200 kPa) and steam-cleaned in a laboratory and cleaned with ethanol and air drying chair-side. Dual-polymerizing, self-adhesive, universal resin cement (RelyX Unicem; 3M Deutschland GmbH, Germany) was used for definitive cementation of the restorations. All the patients were re-called for a check-up six months after the definitive cementation.

4.5 Early complications and short-term failures (Paper I)

The patient records of all the treated patients were searched for recorded complications or failures. Any complications recorded from the beginning of prosthetic treatment to the day of definitive cementation were registered from the patient records (early complications). Any failures during the first year after the definitive cementation were also recorded from the patient records (short-term failures). Early complications and short-term failures were divided into biological and technical subcategories.

4.6 Clinical follow-up

All the treated patients were to be invited to the clinical follow-ups 2–7 years after definitive cementation. Some of the patients could not be reached. The follow-up consisted of a questionnaire and a clinical examination.

4.6.1 Zirconia single crowns (Paper II)

The distribution of 268 zirconia single crowns in dentition is shown in Fig. 3. Of all the patients, 54% had received three or four crowns but there were also patients treated with up to 12 crowns.

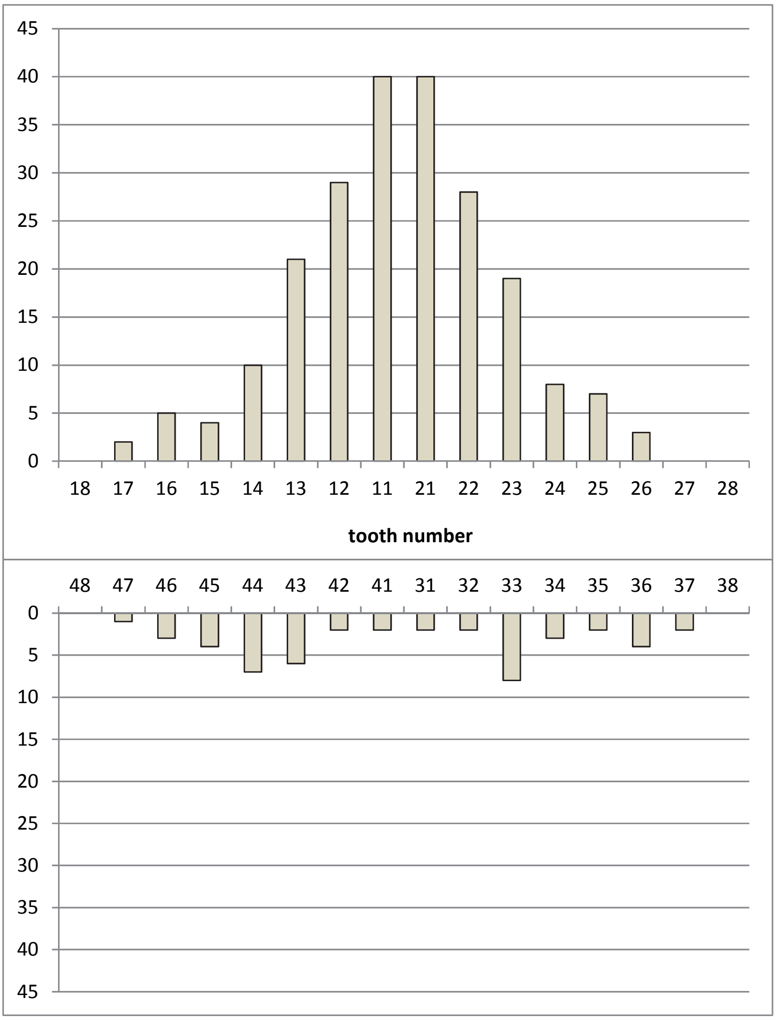

Fig. 3. Distribution of zirconia single crowns (n=264) in dentition.

Of the total of 88 patients, 12 had moved away and one had died. Altogether 75 patients were invited to a clinical follow-up in 2013. Nine patients did not attend and did not contact us. A total of 66 (75%) participants (30 women and 36 men) attended the clinical follow-up and altogether 204 zirconia single crowns (mean 2.9 crowns, range 1–10 crowns) had been prepared for them between 2007 and 2010. In all 14 crowns had been lost during the follow-up period and 190 single crowns were examined. The mean age of the participants was 60.4 years (range 19–81 years) and the mean follow-up time was 3.9 years (1.9–6.0 years).

4.6.2 Veneered zirconia crowns as abutment teeth for partial removable dental prostheses (Paper III)

Altogether 37 veneered zirconia single crowns were prepared for 17 patients (9 men and 8 women; mean age 62.5 years) to serve as abutment teeth for a clasp-retained RDP with a metal framework. The mean follow-up time was 4.2 years (2.9–5.4 years).

4.6.3 Zirconia fixed dental prostheses (FDPs) (Paper IV)

The 120 zirconia FDPs fabricated consisted of 527 total units, of which 342 were abutments and 185 pontics. The distribution of abutments and pontics in dentition is shown in Fig. 4.

Of the 102 patients who had received zirconia FDPs, one had moved away, two had died and four had no contact details available. An invitation letter was sent to 95 patients. Nineteen patients did not attend and did not contact us and 76 (75%) patients (48 women, 28 men) finally attended the clinical examination. In all 88 FDPs had been fabricated, including 250 abutments and 137 pontics. The mean follow-up time was 4.9 years (range 3–7 years).

The FDPs were divided into anterior FDPs from canine to canine and posterior FDPs (premolar and molars). Altogether 40 FDPs had been fabricated for the anterior region and 48 FDPs for the posterior region. The FDPs were also divided into short- and long-span FDPs according to span length (Fig. 5). Short-span FDPs consisted of three or four units, whereas long-span FDPs had five or more units. The vast majority of FDPs (80 FDPs, 67%) were three or four units (range: 3–12 units, mean: 4.5 units) but three 10-unit, one 11-unit and one 12-unit FDPs were also fabricated. The number of restorations according to the length of the restoration is shown in Fig. 5.

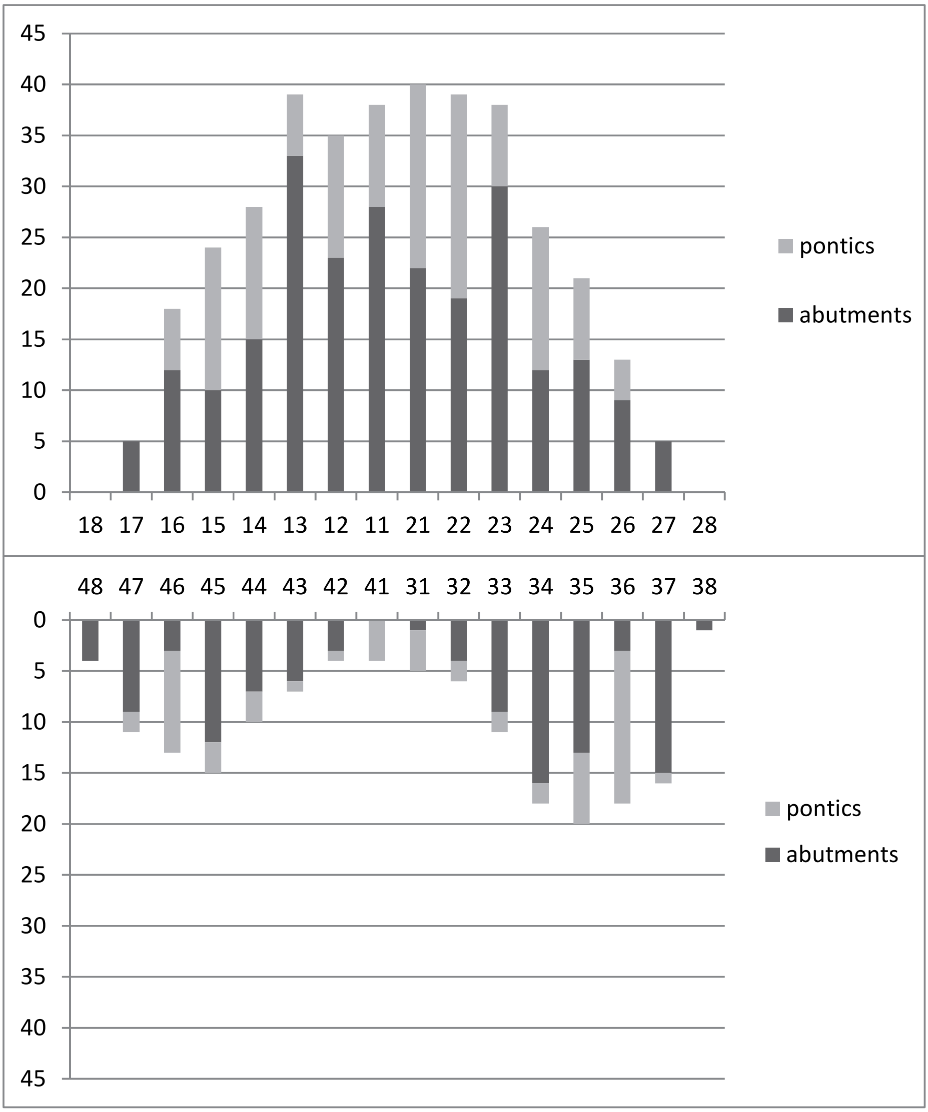

Fig. 4. Distribution of abutments and pontics in dentition. FDPs were divided into anterior FDPs (from canine to canine) and posterior FDPs (premolars and molars) according to the location of abutments and pontics.

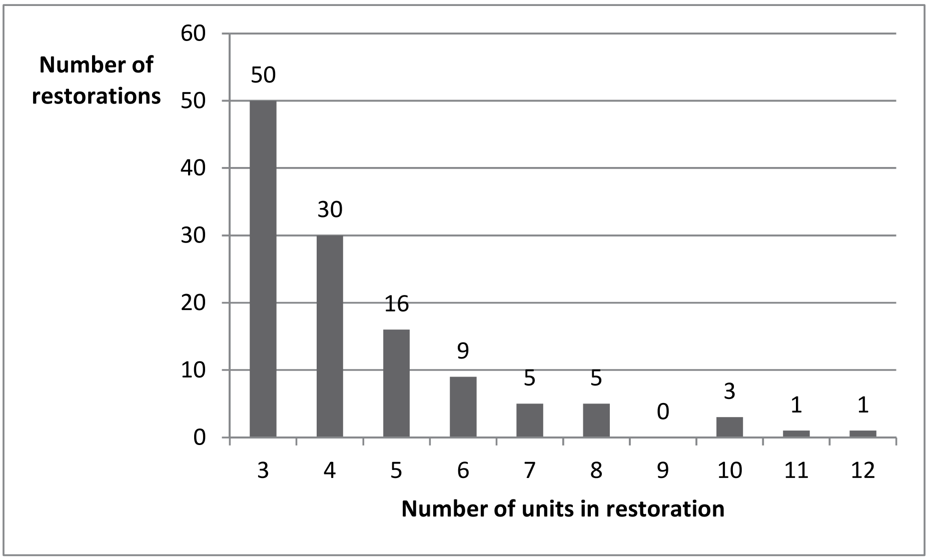

Fig. 5. Zirconia FDPs were divided into short- and long-span FDPs according to span length. A vast majority of the FDPs were short-span FDPs that consisted of three or four units. Long-span FDPs had five or more units.

4.6.4 Clinical follow-up examination

Before the clinical examination, the participants filled in a questionnaire in which they were asked on a Yes or No basis whether they were satisfied ("Are you satisfied with...") with the aesthetics, colour-match, contour, and gloss of the restoration. Personal symptoms such as pain (tooth, masticatory muscles, temporomandibular joints), hypersensitivity to cold or heat and gingival bleeding were also evaluated on a Yes or No basis ("Have you noticed..."). The participants were also asked whether they had had complications or failures with the restoration. The presence of sleep or awake bruxism as defined by Lobbezoo *et al.* (2013) was registered on a Yes or No basis.

In the clinical examination, modified World Dental Federation (FDI) clinical criteria (Hickel *et al.* 2010) were used to evaluate the restorations. The colour match of the restoration, marginal integrity, secondary caries, restorations in the restoration margins, marginal discolouration, anatomic contour (under- and over-contouring), surface texture, chipping or fractures of porcelain and wear of restorations or antagonists were recorded and evaluated as good, acceptable, or unacceptable (Hickel *et al.* 2010). Possible porcelain fractures were divided into grade 1 (polished), grade 2 (repaired with composite-resin), and grade 3 (replaced) according to Anusavice (2012). Retention of the restoration was also checked and evaluated as firmly fixed or loss of retention.

The status of the periodontium of abutment and contralateral teeth was evaluated by plaque accumulation (plaque index) and bleeding on probing (sulcus bleeding index) according to Silness & Löe (1964) and Mombelli *et al.* (1987). Plaque accumulation was divided into three categories: no detection of plaque, plaque only detected by a probe or plaque seen with the naked eye. Bleeding on probing was evaluated as no bleeding when the gingival margin was explored with a periodontal probe, isolated bleeding when explored with a periodontal probe or confluent bleeding when explored with a periodontal probe. The location of the abutment margins (supragingival, marginal, subgingival) and the presence of endodontic treatment through the restoration were recorded. No radiographic evaluations were done as no clinical reasons existed to justify them.

If the restoration served as an abutment tooth for a partial removable dental prosthesis (RDP), the surface of the ceramic rest seat was evaluated as good if intact, acceptable if it showed mild or moderate wear and unacceptable if it had fractures or severe wear. The stability and retention of the RDPs were evaluated as good, moderate, or poor according to Molin Thoren & Gunne (2012). Retention was evaluated by applying vertical pulling forces to the RPD. Retention was evaluated as good if no displacement was seen, moderate if there was minor displacement and poor if no retention was noted. Rotational forces were applied to evaluate the stability of the RPD. Stability was evaluated as good if the RDP firmly resisted rotational forces, moderate if vertical movement was seen after forces were applied and poor if the RDP loosened when rotational forces were applied.

If dental problems were noted at the follow-up, the participants were advised to contact own dentist or book additional appointments at the clinic.

4.7 Statistical analysis

The mean and range were used to describe variables such as the age of the patients and the number or length of restorations. Frequencies and percentages were used to describe the distribution of variables such as gender, complications and failures. Histograms were used to describe variable distribution.

Statistical analysis was performed with computer software (IBM SPSS Statistics 22; IBM, USA). Fisher's exact test (α=.05) was used to evaluate the plaque accumulation index and bleeding on probing index of the abutment teeth and the contralateral teeth. The survival and success of the restorations were calculated using Kaplan-Meier analysis. The longevity of the restoration was measured from the day of definitive cementation to the day of a complication or to the day of a follow-up visit. According to Tan *et al.* (2004), a successful restoration remains unchanged over the observation period, whereas a survived restoration is still *in situ* at the examination visit, regardless of possible reversible complications.

5 Results

5.1 Early complications (Paper I)

Early biological and technical complications during the prosthetic treatment are shown in Table 3. The most common biological complications were localized gingival irritation (1.9% of single crowns and 2.5% of FDPs) and postoperative tooth sensitivity (0.4% of single crowns and 3.3% of FDPs). The most common technical complication during the prosthetic treatment was unacceptable colour leading to a remake of three (1.1%) of the 264 single crowns and one (0.8%) of the 120 FDPs. Unfitting frameworks were recorded in three (2.5%) of the 120 FDPs. No pulp exposure was recorded in 264 single crowns but in 3/342 abutment teeth of FDPs (0.9% of abutments), pulp exposure during preparation had led to capping of the pulp with mineral trioxide aggregate (two abutments) and one abutment had been endodontically treated.

Table 3. Early complications during prosthetic treatment of zirconia single crowns (n=264) and partial FDPs (n=120).

Complication type	Complication description	Single crown		FDPs[1]	
		n	%	n	%
Biological	Localized gingival irritation	5	1.9	3	2.5
	Postoperative tooth sensitivity	1	0.4	4	3.3
Technical	Unacceptable final colour	3	1.1	1	0.8
	Framework did not fit	0	0	3	2.5
	Perforation during preparation	0	0	3	2.5
	Restoration left with temporary cement	0	0	2	1.7
	Loss of existing filling	1	0.4	0	0
	Total	10	3.8	16	13.3

[1]FDP, fixed dental prosthesis.

5.2 Short-term failures (Paper I)

Short-term failures, recorded during the first year in use after the definitive cementation, are shown in Table 4. No biological short-term failures, i.e. periapical, cariological or periodontal failures, of single crowns or FDPs were recorded.

The most common short-term technical failures were chipping of the veneering porcelain and framework fractures (Table 4.) Chipping of the veneering porcelain in two crowns (0.8%) had occurred during the first month after definitive cementation and was considered unrepairable (Grade 3) leading to refabrication of the crowns. Chipping of the veneering porcelain in one FDP was diagnosed as reparable (Grade 2) and was repaired with composite resin. Catastrophic fractures of the framework during the first year occurred in 2 (1.7%) out of the 120 FDPs. One crown with a loss of retention was recemented, whereas none of the 120 FDPs had lost retention during the observation period.

Table 4. Short-term failures in year after definitive cementation of zirconia single crowns (n=264) and partial FDPs (n=120).

Complication type	Complication description	Single crown		FDP[1]	
		n	%	n	%
Biological	–	0	0	0	0
Technical	Porcelain chipping, irreparable	2	0.8	0	0
	Porcelain chipping, reparable	0	0	1	0.8
	Framework fracture	0	0	2	1.7
	Loss of retention	1	0.4	0	0
	Total	3	1.1	3	2.5

[1]FDP, fixed dental prosthesis.

5.3 Clinical findings at the follow-ups

5.3.1 Zirconia single crowns (Paper II)

Overall satisfaction of the patients was high: 98% were satisfied with aesthetics, 95 % with colour-match and contour and 100% with the gloss of the zirconia single crowns. Hypersensitivity to cold in abutment teeth was described by three participants and three participants had noticed gingival bleeding. One participant described pain related to the zirconia crown. Self-reported bruxism was reported by 26 participants.

Less plaque was seen on the zirconia crowns than on contralateral teeth, but with no statistical significance (P=.376) Bleeding on probing was more frequent in teeth with zirconia crowns (P=.012) than in contralateral teeth. The plaque index and sulcus bleeding index are shown in Tables 5. and 6. The crown margin placement was marginal in 53%, subgingival in 43% and supragingival in 4% of the single crowns. Anatomic contour of the zirconia single crowns was rated good in 156/190 (82%) and acceptable in 34/190 (18%) of the crowns. Marginal integrity was rated good in all of the single crowns, whereas marginal discolouration (acceptable) was noted in 3/190 (1.6%) of the single crowns. The occlusal contact surface of 83/190 (44%) zirconia crowns was evaluated as acceptable due to a slightly rough surface. Wear of opposing dentition related to zirconia restorations was suspected with 11/190 (6%) single crowns.

Table 5. Plaque accumulation (Silness & Löe 1964, Mombelli *et al.* 1987) in abutment teeth with zirconia single crowns (n=190) and in contralateral teeth.

Plaque index	Abutment teeth (%)	Contralateral teeth (%)
No detection of plaque	77	41
Plaque only recognized by running a probe across the marginal surface of the crown	17	56
Plaque can be seen by the naked eye	6	3

P=.376; Fisher exact test.

Table 6. Bleeding on probing (Silness & Löe 1964, Mombelli *et al.* 1987) around teeth with zirconia single crowns (n=190) and contralateral teeth.

Bleeding on probing	Abutment teeth (%)	Contralateral teeth (%)
No bleeding when a periodontal probe is passed along the gingival margin	49	39
Isolated bleeding when a periodontal probe is passed along the gingival margin	40	60
Confluent bleeding when a periodontal probe is passed along the gingival margin	11	1

P=.012; Fisher exact test.

Biological and technical complications recorded at the clinical examination are shown in Table 7. The complications of the zirconia single crowns were divided according to manufacturers. No secondary caries or endodontic treatment performed through the zirconia crowns were found in the examination. The most frequent complications were loss of cementation (5%) and chipping of the veneering porcelain (4%). According to Anusavice (2012), three of the porcelain fractures were grade 3 fractures (severe) requiring replacement of the crowns and six were polishable grade 1 fractures that did not affect function or aesthetics. The success rate of the zirconia single crowns was 80% and the survival rate was 89% after four-year (2–6 years) follow-up time.

Table 7. Complications in 204 zirconia single crowns.

Complication type	Complication	Zirkonzahn		NobelProcera		Prettau		Total	
		n	%	n	%	n	%	n	%
No complication	No complication	138	84	17	81	18	95	173	85
Biological	Secondary caries	0	0	0	0	0	0	0	0
	Endodontic treatment through the restoration	0	0	0	0	0	0	0	0
	Root fracture	3	2	0	0	0	0	3	2
	Periapical endodontic infections	2	1	0	0	0	0	2	1
	Total	5	3	0	0	0	0	5	3
Technical	Porcelain fracture, grade 1	5	3	1	5	0	0	6	3
	Porcelain fracture, grade 2	0	0	0	0	0	0	0	0
	Porcelain fracture, grade 3	2	1	1	5	0	0	3	1
	Loss of cementation (recemented)	5	3	2	9	1	5	8	4
	Loss of cementation (loss of crown)	3	2	0	0	0	0	3	2
	Change in treatment plan	6	4	0	0	0	0	6	3
	Total	21	13	4	19	1	5	26	13
Total		164	100	21	100	19	100	204	100

5.3.2 Veneered zirconia crowns as abutment teeth for partial removable dental prostheses (Paper III)

The clinical assessment of zirconia single crowns as abutment teeth of RPDs is shown in Table 8. Neither secondary caries nor endodontic treatment performed through the occlusal surface of the restoration was recorded. Fracture of the veneering porcelain had occurred in 11% of the crowns and fracture of the occlusal rest seat in 3%. Retention was valuated as good in all the RDPs, but stability was rated moderate in 23% of the RDPs.

Table 8. Clinical assessment of 37 zirconia single crowns as abutment tooth for RDP.

Clinical assessment	No (%)	Moderate (%)	Unacceptable (%)
Chipping of veneering porcelain	86	14	0
Over-contouring	87	13	0
Marginal discrepancy	95	5	0
Wear of ceramic surface in rest seat	100	0	0

5.3.3 Zirconia fixed dental prostheses (Paper IV)

Of the 76 participants, 96% were subjectively fully satisfied with the aesthetics of the restoration: 100% with gloss, 99 % with colour match and 97% with the contour of the restoration. The usual symptoms described by the participants in the questionnaire were dull pain (9 patients, 12%), hypersensitivity to cold (8 patients, 11%), and gingival bleeding (4 patients, 11%). Altogether 28/76 (37%) participants reported bruxism in the questionnaire.

Less plaque was seen on abutment teeth of FDPs than on contralateral teeth ($P<0.05$), but bleeding on probing was more frequent in abutment teeth than in contralateral teeth ($P<0.05$).Placement of abutment margins was 65% marginal, 22% subgingival and 14% supragingival. Anatomic contour of abutment teeth of FDPs was rated good in 234/250 (94%) and acceptable in 16/250 (6%) abutments of FDPs. Marginal integrity was good in all of the abutment teeth whereas marginal discolouration was rated acceptable in 3/250 (1.2%) of abutment teeth. The occlusal contact surface of 23/88 (26%) zirconia FDPs was evaluated as acceptable due to a slightly rough surface. Wear of opposing dentition related to the zirconia FDP was suspected in 7/88 (8%) FDPs.

Complications of the zirconia FDPs are shown in Table 9. The survival rate of the zirconia fixed dental prostheses was 100% and the success rate was 89% after five years. None of the 88 FDPs had lost cementation during the observation period and no secondary caries was found, either. Endodontic periapical infection had led to endodontic treatment through the occlusal surface of an abutment tooth in one FDP.

Chipping of the veneering porcelain was noticed in 13 units (11 patients), of which seven were in anterior and five in posterior regions. The distribution of veneering porcelain fractures is shown in Table 10. and Fig. 6. Nine of the chippings were in long-span FDPs and four in short-span FDPs. Of these porcelain fractures, 12 were easily polished without aesthetically compromising appearance and therefore evaluated as a grade 1 fracture according to Anusavice

(2012). In one FDP a fracture in the first incisor had been repaired with composite-resin, compromising the appearance of the restoration and therefore was evaluated as a grade 2 fracture (Anusavice 2012).

Table 9. Complications in 88 zirconia FDPs.

Complication type	Complication	Zirkonzahn		NobelProcera		Prettau		Total	
		n	%	n	%	n	%	n	%
No complication	No complication	63	83	5	83	6	100	74	84
Biological	Secondary caries	0	0	0	0	0	0	0	0
	Endodontic treatment through the restoration	0	0	0	0	0	0	0	0
	Root fracture	0	0	0	0	0	0	0	0
	Periapical endodontic infections	1	1	0	0	0	0	1	1
	Total	1	1	0	0	0	0	1	1
Technical	Porcelain fracture, grade 1	11	15	1	17	0	0	12	14
	Porcelain fracture, grade 2	1	1	0	0	0	0	1	1
	Porcelain fracture, grade 3	0	0	0	0	0	0	0	0
	Loss of cementation (recemented)	0	0	0	0	0	0	0	0
	Loss of cementation (loss of crown)	0	0	0	0	0	0	0	0
	Change in treatment plan	0	0	0	0	0	0	0	0
	Total	12	16	1	17	0	0	13	15
Total		76	100	6	100	6	100	88	100

Table 10. Distribution of veneering porcelain fractures (n=13) in FDPs (n=88) according to span length, jaw, and region of fracture.

Region	Span length	Maxilla (n=61)	Mandibula (n=27)	Total (n=88)
anterior region	3-4 unit FDPs (n=18)	3	0	3
FDPs (n=40)	over 5 unit FDPs (n=22)	3	2	5
posterior region	3-4 unit FDPs (n=40)	1	0	1
FDPs (n=48)	over 5 units FDPs (n=8)	3	1	4
total (n=88)		10	3	13

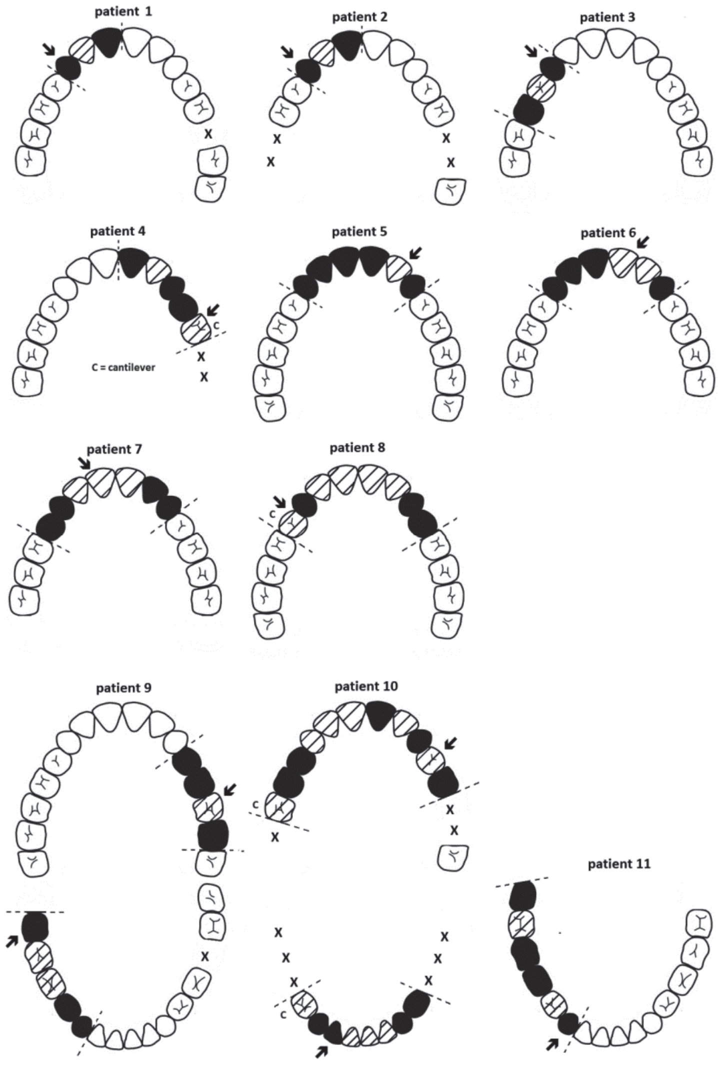

Fig. 6. Chipping of veneering porcelain (n=13) recorded in 11 patients. Arrows indicate site of chipping, abutments are shown in black, pontics are rasterized and missing teeth are marked "X". Patients 1-8. had chipping in maxilla, patients 9. and 10. both in maxilla and mandible, and patient 11. in mandible.

6 Discussion

6.1 Material and methods

The material of the study consisted of 173 patients treated with zirconia restorations by predoctoral dental students between 2007 and 2010 at the Dental Training Clinic, Oral Health Services, City of Oulu. Altogether 88 patients had received zirconia single crowns and 102 patients had received zirconia FDPs. According to literature, this is one of the largest materials of clinical studies related to zirconia restorations (Al-Amleh *et al.* 2010, Raigrodski *et al.* 2012a, Larsson & Wennerberg 2014, Pjetursson *et al.* 2015, Sailer *et al.* 2015). However, the retrospective nature of the clinical study caused some difficulties in the analysis of the results. The results of the study have to be evaluated with care, because all the original patients were not interested in participating in the clinical follow-up after up to seven years. The reasons can only be suspected, i.e. either dissatisfaction with the restoration or changes in personal circumstances. In Papers II and IV the drop-out rate was 25%. Similar drop-out rates have been noted in other clinical studies related to zirconia restorations (Schmitter *et al.* 2012, Tartaglia *et al.* 2015), but much lower drop-out rates have also been reported (Pjetursson *et al.* 2015, Sailer *et al.* 2015), and especially when patients have been recalled annually (Kern *et al.* 2012, Chaar *et al.* 2015). The drop-out rate here was relatively high, but on the other hand, prosthetic treatment with fixed restorations is expensive and this is why it can be expected that patients who have had problems would have contacted Oral Health Services, City of Oulu.

The relatively short observation period and the lack of a control group are also study limitations. It would have been beneficial to be able to compare the results with metal ceramic restorations that were fabricated during the same period at the Dental Training Clinic. The study was started in 2012 and at that time there were only a few 4–5-year clinical follow-ups on zirconia crowns and FDPs with moderate size study populations. The failure rate is expected to increase after a longer observation period (Rinke *et al.* 2013b, Sax *et al.* 2011), although different results have also been reported (Håff *et al.* 2015, Tartaglia *et al.* 2015). Rinke *et al.* (2013b) reported a decrease in the survival rate of 94% at a four-year follow-up to 83.4% at a seven-year follow-up and an increase in the annual failure rate from 1.5% to 3.3%. On the contrary, Solá-Ruíz *et al.* (2015) concluded that if a zirconia restoration survived three years without complications, it more likely survived the seven-year follow-up time without complications. Another limitation of this study is the impossibility to reliably compare monolithic zirconia system with veneered zirconia systems or veneered zirconia systems with each other because the number of these restorations was low.

The pre-prosthetic and prosthetic treatments were performed by predoctoral dental students. This reflects the usefulness of zirconia restorations, as all the treatments were performed by unexperienced students, early complications during prosthetic treatment were few and the survival and success rates are comparable with other clinical studies. All the patients treated with zirconia restorations between 2007 and 2010 were invited to the clinical examination, no exclusion was performed and all the restorations were evaluated by the same examiners using the same clinical criteria.

6.2 Patient satisfaction

Satisfaction with the aesthetics and function of the zirconia restorations in this study was high. A few complaints about aesthetics regarded colour match and bulky contour, whereas complaints regarding function were related to biting of the cheek mucosa. These results are in accord with other clinical studies reporting high satisfaction with veneered zirconia restorations (Molin & Karlsson 2008, Sorrentino *et al.* 2012, Håff *et al.* 2015, Nejatidanesh *et al.* 2016). In literature, opaqueness is depicted as a negative feature of zirconia, but overall satisfaction regarding aesthetics seems to be high. It has to be taken into consideration, however, that the mean age here was 55, and the aesthetic demands of elder patients are usually lower.

6.3 Biological complications and failures

Early biological complications during prosthetic treatment were few and temporary. Only a little more localized gingival irritation and postoperative tooth sensitivity was noted in the zirconia FDPs than in single crowns. Localized gingival irritation was generally caused by excess cement. No biological short-term failures had occurred during the first year of use. Tooth sensitivity during preparation was reported as temporary and needed no additional treatment, except in two cases in which the FDP had been left with temporary cement for a longer period of time to monitor symptoms. Roediger *et al.* (2010) also described tooth sensitivity as a common but transient symptom and Monaco *et al.* (2013) reported that 8% of vital abutment teeth had temporary symptoms of tooth sensitivity.

In this study no secondary caries was observed. In recent meta-analyses, a significantly higher rate of secondary caries had been reported for zirconia single crowns and FDPs (Pjetursson *et al.* 2015, Sailer *et al.* 2015). On the contrary, no secondary caries had been reported after five years in several studies (Molin & Karlsson 2008, Schmitter *et al.* 2012, Monaco *et al.* 2013 Nejantidenesh *et al.* 2015). Monaco *et al.* (2013) reported no secondary caries in 1132 zirconia single crowns after five years. Tartaglia *et al.* (2015) reported a failure rate of 0.7% due to secondary caries after seven years.

In this study no marginal discrepancies and only a few marginal discolourations were found. The high rate of secondary caries in some studies is likely related to the poor marginal fit of these restorations due to early-stage prototype CAM systems. Sax *et al.* (2011) reported a high rate of marginal discrepancy and secondary caries when a prototype CAM system (direct ceramic machining, DCM) was used. Rinke *et al.* (2013b) noted that they started the study as early as 2001 and an early-stage CAM system was used. Roediger *et al.* (2010) noted a decrease in the rate of secondary caries after a software update of CAD/CAM system. In this study, newer versions of CAD/CAM systems were used for dental education should reflect new trends in dental practice, but the materials and techniques should also be reliable and relatively easy to handle. A problem in analysing review articles is that they can overestimate some problems as they do not always take into account the developments within the materials and fabrication techniques.

More plaque was seen on contralateral teeth than on abutment teeth, but more bleeding on probing was seen with abutment teeth, which indicates that bacterial adhesion is not the only factor affecting periodontal health. Other major factors that damage the periodontium are compromised biological width and improper reproduction of the dental contour (Becker & Kaldahl 2005, Vasconcelos *et al.* 2009). No significant differences regarding periodontal health between abutment teeth and control teeth have been found in other studies (Tinschert *et al.* 2008, Edelhoff *et al.* 2008, Beuer *et al.* 2009, Sailer *et al.* 2009a, Beuer *et al.* 2010, Roediger *et al.* 2010, Monaco *et al.* 2013, Håff *et al.* 2015). Örtorp *et al.* (2009) reported that gingival bleeding and calculus were evident with 17/25 crowns after three years.

In this study, anatomic contour was rated as slightly over-contoured (acceptable) in 18% of single crowns and in 6% of abutment teeth of FDPs. Molin

& Karlsson (2008) reported slight over-contouring in 5-10% of zirconia FDPs. Under-contouring of buccal and lingual surfaces may promote gingival health, whereas a bulky restoration may damage the periodontium, possibly because it obstructs cleaning, and therefore buccal and lingual contours should be kept flat (Becker & Kaldahl 2005). Adequate tooth preparation (dimensional requirements of the restorative materials) and being familiar with crown morphology (both dentist and technician) are essential for proper reproduction of the dental contour (Becker & Kaldahl 2005). Of the restoration margins, 57% were placed marginally or supragingivally and 43% subgingivally in single crowns, whereas 79% of margins were marginal or supragingival in FDPs. Plaque accumulation, inflammation and gingivitis have been reported to be more frequent in teeth with subgingival crown margins than with supragingival margins (Becker & Kaldahl 2005, Podhorsky *et al.* 2015). A subgingival restoration margin may compromise biological width and cause chronic inflammation in the periodontium (Podhorsky *et al.* 2015). The type of subgingival finish line may have an effect on periodontal health (Paniz *et al.* 2015).

Patients treated with conventional fixed prosthodontics should undergo thorough removal of excess cement and professional cleaning and should be given improved home instructions. Studies have concluded that proper home care is more important than the choice of restorative material in terms of bacterial adhesion (Litonjua *et al.* 2012). All the patients in this study received cariological, periodontal, and endodontic treatment prior to prosthetic treatment, if needed. Professional tooth cleaning, including education and instructions for proper home care, was performed on all the patients.

6.4 Technical complications and failures

6.4.1 Technical early complications

There were few technical complications during the prosthetic treatment. The most common complications were unacceptable colour, poor fit of the framework, and pulp exposure during preparation. Pulp exposure during preparation did not occur in preparation of the single crowns, but the pulps of 3/342 (0.9%) abutment teeth of the FDPs were exposed. This is comparable with metal ceramic FDPs as Raustia *et al.* (1998) reported 2/221 (0.9%) perforations during preparation of abutment teeth for metal ceramic FDPs.

In this study, a deep chamfer finish line was used, but some studies have indicated that a knife-edge margin is also suitable preparation for zirconia and other ceramic materials with less removal of tooth substance (Schmitt *et al.* 2010, Cortellini & Canale 2012, Monaco *et al.* 2013). No margin preparation design has been proven to be more durable or better fitting than other designs (Podhorsky *et al.* 2015). Preparation design should be chosen with regard to the specific clinical situation. In situations where preservation of sound tooth substance is required, a knife-edge margin might have more benefits than a chamfer or shoulder finish line (Monaco *et al.* 2013). The visibility of the margin by a technician or with a scanning device should be considered when choosing the margin preparation (Podhorsky *et al.* 2015). Mini-invasive techniques are coming to fixed prosthodontics, but adhesive bonding is needed in those cases.

6.4.2 Technical short-term failures

In this study, short-term failures were chipping of the veneering porcelain, loss of retention and framework fractures. The two chippings in crowns had occurred within the first few weeks after cementation, and were diagnosed as unrepairable, grade 3 chippings according to Anusavice (2012). The crowns were remade. Chipping in FDP was considered Grade 2 chipping and was repaired with composite resin. None of the FDPs, but 1/264 (0.4%) of the crowns had lost retention and was recemented.

If the material fails shortly after definitive cementation, the failure is likely caused by material weakness or errors during the fabrication process. At this point, patient-related factors such as bruxism or diet are only minor factors. Identifying these possibly rectifiable initial problems is important, because studies have indicated that an early repairable complication is a risk factor for unrepairable failure later (De Backer *et al.* 2006a, De Backer *et al.* 2006b). Sagirkaya *et al.* (2012) found in a four-year follow-up of zirconia FDPs that four out of five failures occurred during the first year. Sola-Ruiz *et al.* (2015) found that if the zirconia FDP survived the first three years without complications, the risk for failures during a seven-year follow-up period decreased.

Framework fracture was noted in 2/120 (1.7%) FDPs and the restorations were remade. The first framework fracture had occurred at the six-month recall when an attempt was made to remove the FDP that had been left with temporary cement (sensitivity problems). The other framework fracture occurred for an unknown reason shortly after definitive cementation in an occlusal area of a molar abutment tooth. A new FDP was remade and was still *in situ* at the follow-up meeting.

6.4.3 Chipping

Most of the chippings of the veneering porcelain noted at the clinical examination were polishable. It was noticed that the majority of the chippings had occurred on occlusal surfaces, and they were possibly related to advanced wear of the surface. Similar findings have been made in other studies (Sailer *et al.* 2009a, Koenig *et al.* 2013). Most of the porcelain fractures were found during the follow-up and the participant had not noticed it. Most of the chippings could be polished without compromising esthetics and function. It has been noted in other studies that chippings are usually incidental findings during follow-ups and rarely leads to renewal of the restoration (Sax *et al.* 2011, Schmitter *et al.* 2012, Rinke *et al.* 2013b). Nejatidanesh *et al.* (2016) reported chipping of the veneering porcelain in 45/556 zirconia single crowns, of which 42 were minor and could be polished without compromising aesthetics and function.

A porcelain veneer on zirconia seems to be more fragile than on metal (Augstín-Panadero *et al.* 2012). In metal ceramic restorations the fracture usually occurs at the metal-porcelain interface, whereas with zirconia restorations the fracture usually occurs within the porcelain veneer (Schmitt *et al.* 2011, Augstín-Panadero *et al.* 2012) and is cohesive in nature (Fischer *et al.* 2008, Schmitt *et al.* 2011, Preiss *et al.* 2013). There is evidence that cohesive porcelain fractures are related to a compressive stress induced by overly fast cooling after firing and can be prevented by using a slower cooling procedure (Denry & Kelly 2014, Paula *et al.* 2015) Nowadays, most porcelain veneer manufacturers have modified firing guidelines for zirconia restorations (Paula *et al.* 2015). Promising clinical results have been seen when an anatomical design of the framework and a slow cooling protocol have been adopted (Örtorp *et al.* 2012, Rinke *et al.* 2013a, Rinke *et al.* 2016, Tartaglia *et al.* 2015).

6.4.4 Loss of retention

None of the 88 FDPs, but 8/204 (4%) of the zirconia single crowns lost retention during the follow-up period. Recent meta-analyses by Sailer *et al.* (2015) and Pjetursson *et al.* (2015) reported significantly more loss of retention for zirconia single crowns and FDPs than for metal ceramic restorations. This was argued to be related to inaccuracies in the fit of the framework. Another factor that may explain the loss of retention issue could be differences in the preparation designs of metal ceramic and zirconia abutments. In some studies, different findings have been made, as Tartaglia *et al.* (2015) reported that 3/130 (2.3%) zirconia single crowns and 0/49 (0%) zirconia FDPs had lost retention after seven years and Monaco *et al.* (2013) described only 2/1127 (0.2%) losses of retention after five years.

Strong and durable adhesive cementation increases retention and fracture resistance and improves marginal adaptation of the restoration (Thompson *et al*. 2011). Cleaning and roughening the inner surface of the zirconia restoration with moderate-pressure airborne-particle abrasion and cementation with phosphate monomer-containing primer or luting resin seem to provide a durable bond to zirconia (Sasse & Kern 2013, Kern 2015). These bonding procedures were not completely followed in this study, as the adhesive cement used here did not contain MDP monomer. To date, zirconia has mostly been cemented with conventional cements like zinc phosphate or with glass-ionomer or resin-based cements without MDP monomer. It seems that strong and durable adhesive cementation is needed to increase the retention of zirconia restorations, especially single crowns, and zirconia bonding procedures (Kern 2015) are therefore recommended.

6.4.5 Wear of the restoration and antagonist teeth

In this study, a slightly rough occlusal surface was a common find. Clinical follow-up studies have revealed a high incidence of occlusal surface roughness in the veneering porcelain of zirconia restorations Molin & Karlsson 2008, Sailer *et al.* 2009a, Schmitt *et al.* 2011, Koenig *et al.* 2013). It was reported by Schmitt *et al.* (2011) that after 48 months 59% of the units of zirconia FDPs were evaluated clinically as slightly rough or pitted and 65% after evaluation with a scanning electron microscope (SEM). The glaze is worn away over time (Heintze *et al.* 2008, Janyavula *et al.* 2013). Some studies recommended repolishing the zirconia restorations at recall visits (Sax *et al.* 2011, Sripetchdanond & Leevailoj 2014)

Veneering porcelain is reported to be more abrasive than natural enamel or zirconia (Kim *et al.* 2012, Burgess *et al.* 2014, Lawson *et al.* 2014). Wear of opposing dentition was not a major problem in this study, but may increase due to a roughened porcelain surface. The surface roughness of ceramic restorations seems to increase enamel wear of the antagonist tooth (Ghazal & Kern 2009). Lawson *et al.* (2014) even recommended avoiding porcelain on the occlusal contact area to prevent enamel wear of antagonist teeth. Promising clinical results have been seen with monolithic and minimally veneered zirconia restorations (Moscovitch 2015, Venezia *et al.* 2015).

6.4.6 Veneered zirconia crowns as abutment teeth for partial removable dental prostheses

The lack of strength has contraindicated the use of all-ceramic materials in removable partial denture (RPD) abutments (Kancyper *et al.* 2000, Carracho & Razzoog 2006). The excellent physical properties of zirconia would allow the use of tooth-coloured single crowns in these situations, but no clinical studies existed to confirm this hypothesis. In this study no wear was seen on zirconia surface of the occlusal rest seat, but chipping of the veneering porcelain was a common problem. The occlusal rest in a zirconia single crown is more rounded than in metal ceramic crowns because of material-related factors, but stability and retention were rated good in most of the RDPs. The usefulness of monolithic zirconia should be evaluated or veneering porcelain should be applied only to non-functional areas, as described by Venezia *et al.* (2015).

6.5 Success and survival of zirconia single crowns and fixed dental prosthesis

In this study, the survival rate of zirconia single crowns after 3.9 years was 89% and the success rate was 80%, whereas the survival rate of zirconia FDPs after 4.9 years was 100% and the success rate was 89%. The results agree with clinical follow-up studies, as in recent meta-analyses the estimated five-year survival rate of zirconia single crowns in the anterior region was 98.5% and it was 95% in the posterior region, and the estimated five-year survival rate of zirconia FDPs was 90.4% (Pjetursson *et al.* 2015, Sailer *et al.* 2015). In the studies with a follow-up time of at least four years, the survival rates of zirconia single crowns have varied from 91% to 98% (Beuer *et al.* 2010, Schmitt *et al.* 2010, Sagirkaya *et al.* 2012, Örtorp *et al.* 2012, Monaco *et al.* 2013, Rinke *et al.* 2013b, Nejatidanesh *et al.* 2016, Rinke *et al.* 2016, Tartaglia *et al.* 2015) The survival rates of zirconia FDPs has varied from 94% to 100% after four to five years (Molin & Karlsson 2008, Wolfart *et al.* 2009, Roediger *et al.* 2010, Schmitt *et al.* 2011, Peleaz *et al.* 2012, Raigrodski *et al.* 2012a, Sagirkaya *et al.* 2012, Sorrentino *et al.* 2012). In the longer 6–10-year follow-ups, the survival rate has varied from 86% to 100% (Lops *et al.* 2012, Rinke *et al.* 2013a, Håff *et al.* 2015Solá-Ruíz *et al.* 2015, Tartaglia *et al.* 2015). Lower survival rates have been reported in a few studies (Sax. *et al.* 2011, Schmitter *et al.* 2012, Passia *et al.* 2013).

In this study, 17/204 single crowns were evaluated as total failures. One participant had lost a crown because of a loss of cementation, two crowns were lost because of a root fracture, and thereafter the treatment plan had been changed to a removable prosthesis and three more crowns had been removed. Another participant had lost a crown because of a root fracture and thereafter three adjacent crowns were removed because of the treatment plan of FDP. It seems that problems accumulate in the same patients and one failure or complication increases the risk for another.

Parafunctional habits like bruxism and endodontic treatment/non-vitality of the teeth have been reported to increase the risk for complications and failures of all-ceramic restorations (van Dijken & Hasselrot 2010, Beier *et al.* 2012). This has also been noted with zirconia crowns, as Monaco *et al.* (2013) found an almost three times higher risk for chipping of the veneering porcelain in endodontically treated teeth with fiber reinforcement or if moderate or severe parafunctional habits were present. They also described that 23/66 patients using an occlusal splint reported delamination or chipping of the veneering porcelain (Monaco *et al.* 2013). Koenig *et al.* (2013) concluded that absence of an occlusal splint, ceramic restoration as an antagonist tooth, and presence of parafunctional habits are statistically significant factors in chipping formation.

In this study, only one participant with porcelain chipping had reported bruxism. It has to be taken into account that bruxism was self-reported here. Low correlation between self-reported sleep bruxism and clinical manifestation of bruxism has been reported in TMD patients (Paesani *et al.* 2013). Oral appliances are a standard treatment for sleep bruxism (Manfredini *et al.* 2015) and are also often recommended after treatment with a fixed prosthesis (Koenig *et al.* 2013), even though it seems that an occlusal splint does not decrease the rate of chipping of the veneering porcelain (Monaco *et al.* 2013).

In this study, the long-span FDPs (five-unit or more) seemed to have an increased risk for chipping of the veneering porcelain. This has been noted in other clinical studies (Sax *et al.* 2011, Solá-Ruíz *et al.* 2015) although only a few studies have examined both short- and long-span FDPs. A meta-analysis of single crowns indicated that a higher risk of technical complications in zirconia crowns is seen in posterior regions than in anterior region (Sailer *et al.* 2015). Different results have also been reported, as in a retrospective cohort study of 1132 zirconia crowns Monaco *et al.* (2013) noted that chippings of veneering porcelain were evenly distributed in the anterior and posterior regions. Rinke *et al.* (2015) found that, within the molar region, a 5.5 times higher risk for chipping was seen if a crown was placed in a terminal abutment i.e. in an abutment with no adjacent teeth distally.

6.6 Zirconia in fixed prosthodontics

The survival and success of zirconia single crowns in this study are comparable, but not superior to the survival of other recent all-ceramic crowns (Sailer *et al.* 2015). If no parafunctional habits exist, the choice of an all-ceramic material for a single crown can be made according to the site of the restoration, taking into account aesthetic and functional demands. From the material point of view, zirconia single crowns cannot be recommended over any other recent ceramic materials.

The survival and success rates of zirconia FDPs here seem to be superior to those of other all-ceramic FDPs. There are follow-up studies available concerning these other all-ceramic FDPs with survival rates comparable to zirconia, but they include only short FDPs in the anterior and premolar regions of dentition (Kern *et al.* 2012, Chaar *et al.* 2015).

From the biological point of view, monolithic or minimally veneered zirconia would be beneficial over other all-ceramic materials as less preparation of the tooth structure is needed. The minimal preparation concept is the future of fixed prosthodontics, potentially also with zirconia materials, because adhesive long-term bonding of zirconia seems promising.

7 Summary and conclusion

The results of the study show that zirconia restorations are a suitable treatment alternative in fixed prosthodontics. Biological complications during prosthetic treatment and follow-up were few. Chipping of the veneering porcelain is common, but in most cases it is a repairable complication. The surface of zirconia restorations should be evaluated with care at recall visits, because chippings seem to be related to advanced wear of the porcelain surface. However, developments in fabrication processes seem to have decreased the rate of chipping, and with new fabrication guidelines chipping may be comparable with metal ceramic restorations. Monolithic and minimally veneered zirconia restorations are a promising treatment alternative, but possible effects on antagonist teeth and long-term low-temperature degradation of unveneered zirconia should be considered. Loss of retention is a common problem with zirconia single crowns, and clinical studies with updated fabrication guidelines and bonding procedures are needed.

Based on the findings of the study, the following conclusions can be drawn:

1. Early complications during prosthetic treatment and short-term failures during the first year of use of zirconia single crowns and fixed dental prostheses (FDPs) were few.
2. The success and survival of zirconia single crowns were found to be comparable, but not superior to other recent ceramic materials.
3. Short- and long-span zirconia FDPs performed well in both anterior and posterior regions of dentition.
4. Zirconia single crowns performed well as abutment teeth for partial RDPs with a metal framework, but fractures in the veneering porcelain remained a problem.

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