Prosthodontic Outcomes of Zirconia Implants Supporting Overdentures

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This doctoral thesis is a culmination of a series of interrelated \textit{in-vivo} and \textit{in-vitro} investigations related to the rehabilitation of fully edentulous patients with maxillary and mandibular overdentures supported by zirconia implants. A novel prosthodontic design based on the need for improved biomechanics with one-piece zirconia implants was evaluated. Most of the associated studies that form the chapters of this thesis have been published in high impact dental journals.

Chapter I is an overview of the existing literature and preamble to the core subject of the research. This chapter is divided into three main parts; the first part provides a brief historical background on different materials available for the fabrication of oral implants. The second part describes the various overdenture designs available in the literature. The third part represents a systematic review of the literature on the maintenance requirements of implant overdentures, with the emphasis on maxillary overdentures, a topic that is under discussed in the literature. Definitions of the research rationale and objectives follow thereafter.

Chapter II presents two \textit{in-vitro} finite element analyses (FEA) studies that were performed prior to the commencement of the actual clinical trial to evaluate the validity of the proposed research questions. The first study compares the biomechanical behavior between zirconia and titanium implants supporting maxillary overdentures. The second FEA simulation investigates the biomechanical aspects of proposed novel prosthodontic designs comprising different implant distributions used to support maxillary overdentures.

Chapter III describes a clinical pilot study investigating the prosthodontic outcomes of zirconia implants supporting maxillary and mandibular overdentures in the context of a novel prosthodontic design (implant distribution). The rationale of the novel design is discussed in this chapter and subsequently further recommendations with regards to other design were made.

Chapter IV is a randomized clinical trial comparing the outcomes of zirconia and titanium implants supporting maxillary and mandibular overdentures, following the novel distribution of implants recommended from the pilot study. Part II of this chapter describes
the prosthodontic maintenance requirements encountered with titanium and zirconia implant overdentures at the end of the 1-year follow-up observation period.

Chapter V describes a scanning electron microscopic study (SEM) of a number of fractured zirconia implants. Based on fractographic analysis, the origins of the fractures were identified and recommendations for modifications to the current designs of available zirconia implants were made to avoid such incidences in the future and improve the biomechanical behavior of zirconia implants.

Chapter VI is a qualitative study based upon semi-structured interviews with participants 9 to 12 months after prosthetic rehabilitation with implant overdentures in order to gain a deeper understanding of the patients’ perception concerning the novel aspects of this treatment modality.

Chapter VII presents a general discussion collating the in-vivo and in-vitro findings of this doctoral research. Evidence-based recommendations for resolving the edentulous predicament with zirconia implant-retained-overdentures are also defined together with recommendations for future research.
Removable implant overdentures have become a widely accepted and well-established treatment modality for the management of edentulous patients. To date, titanium is the biomaterial of choice for the fabrication of oral implants due to its superior mechanical properties and excellent biocompatibility. However, controversial reports about possible allergic reactions to titanium, together with the rise in the concept of “metal-free” dentistry, have propelled the search for alternative implant materials. Of particular interest is zirconia, specifically yttrium-stabilized tetragonal polycrystalline zirconia (Y-TZP). Preclinical studies, case reports and randomized clinical trials on the use of zirconia implants for rehabilitation of partially dentate patients have revealed favorable outcomes, albeit in the short-term. Despite these encouraging results, there is a lack of published literature on the use of zirconia implants for the support of overdentures.

This doctoral thesis aimed to evaluate and compare the clinical and prosthodontic outcomes of similar design zirconia and titanium implants used for the support of maxillary and mandibular overdentures in a randomized controlled trial. A novel protocol for implant distribution was adopted based on the need for improved biomechanics in using zirconia implants. The implant distribution was: in the maxilla, a mid-palatal implant and three anterior implants in the incisor and first premolar regions; in the mandible, a mid-symphyseal implant and bilateral distal implants in the first molar region. The implants were conventionally loaded four months after the surgical procedures.

The overall survival rate for all the implants in this trial was 75.9 %. After one year there was no significant difference in the survival rate between the two groups in either jaw. In the mandible, titanium implants showed a survival rate of 95.8% versus 90.9 % for the zirconia implants ($P=0.47$). The corresponding values in the maxilla were 71.9% and 55% for the titanium and zirconia groups respectively ($P=0.14$). Implants in the maxilla showed a significantly higher failure rate than those in the mandible for both groups ($P< 0.05$). Three implants fractured in the zirconia group.
The bone level changes around the implants were favorable after one year, with marginal bone loss of 0.18 mm for the titanium implants and 0.42 mm for the zirconia implants. A statistically significant difference was noted between the two groups ($P = 0.009$).

Mid-line fracture of the mandibular denture was the most commonly encountered prosthodontic complication. Reduced acrylic thickness around clips and increased masticatory forces were identified as the main reasons for fracture. No statistically significant difference was observed between the two groups ($P > 0.05$).

Fractographic analysis of fractured zirconia implants was used to draw some recommendations regarding the designs of the existing implants and minimize such incidences in the future. Further research to optimize the design of zirconia implants for minimizing placement failures as well as for the support and retention of overdentures is still mandatory.

The qualitative study on the patients’ perception of the proposed treatment revealed that the novel implant protocol was acceptable to patients. The major perceived advantages of the treatment were functional improvement and increased social confidence. Cost was a significant barrier for edentulous patients seeking implant treatment. Participants’ knowledge of implant treatment is limited and should be enhanced.

The \textit{in-vivo} and \textit{in-vitro} findings of this thesis identify the potential use of zirconia implants for the support of overdentures. However, due to the increased marginal bone loss and higher fracture rate observed for zirconia implants compared to titanium ones, the use of zirconia implants should only be limited to patients with allergy to titanium or those requesting a metal-free restoration.
ACKNOWLEDGEMENTS

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I would also like to extend my thanks to my dear friend at the School of Dentistry, Shareen El Shayeab, you have been a sister to me. The precious time we shared together will always be cherished. Yanwei Tan, your presence in the times of need will never be forgotten.
DEDICATION

To Allah the most graceful & the most merciful, thank you for granting me the strength to go through this tough vibrant PhD journey.

To my mum & the candle of my life, words will never give you your right, I owe everything I achieved in life to you, and I hope that one day I can put a smile on your face & into your heart.

To my sister and best friend, thanks for being by my side along the way.
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Journal publications arising from this thesis


7. **Osman**, R.B., Duncan, W., Swain, M.V., Ma, S. Prosthodontic maintenance of maxillary and mandibular overdentures supported by zirconia and titanium implants featuring a novel implant distribution. *Int J Prosthodont [under Review].*
8. **Osman, R.B., Duncan, W., Swain, M.V., Ateih, M., Ma, S.** Ceramic implants (Y-TZP): are they a viable alternative to titanium implants for the support of overdentures? A randomized Clinical Trial. *Clin Oral Implants Res; [Under Review].*
Conference Presentations


CHAPTER I

Review of literature
INTRODUCTION

Over the last decade, implant supported overdentures have become a well-established treatment modality for resolving the edentulous predicament. This treatment offers improved retention and stability compared to conventional complete dentures, resulting in an overall improvement in the quality of life for edentulous patients. Titanium and its alloys have been the biomaterials of choice for the fabrication of oral implants and are expected to remain so in the long-term. However, controversial reports of allergic reactions to titanium and the increasing popularity of the “metal-free” concept in dentistry have propelled the search for alternative implant materials. Bioceramics have been proposed as one of these alternatives due to their exceptional biocompatibility, and excellent biological and physical properties as an implant material. Earlier attempts involved the use of single crystal sapphire and polycrystalline alumina (aluminum oxide) implants (Zetterqvist et al., 1991). However, the inferior mechanical properties and associated clinical outcomes of these systems, compared to titanium-based ones, have limited their popularity.

With the introduction of zirconia, particularly yttria-stabilized tetragonal polycrystalline zirconia (Y-TZP), interest in ceramics as a material of choice has been renewed. Zirconia exhibits good physical and mechanical properties, such as a high flexural strength (900 – 1200 MPa), hardness (1200 Vickers) and Weibull modulus (10-12). A unique characteristic of Y-TZP is stress induced transformation toughening, in which phase transformation results in local volume expansion that counteracts crack propagation.

Current in-vitro and in-vivo studies, case reports and randomized controlled trials on zirconia implants for the rehabilitation of partially dentate patients have revealed favourable outcomes, albeit in the short-term. However, similar data on the use of zirconia implants for the support and retention of overdentures is lacking.

Acknowledging the brittle nature of ceramics, special attention should be given not only to the design of the implants but also to their distribution throughout the arch. Implant configuration has been reported to be one of the factors that influence the load distribution at the bone-implant interface during function. A favourable biomechanical environment is a prerequisite for enhancing the mechanical integrity of implants, ensuring an optimal osseointegration and therefore achieving long-term prognosis of dental implants. With this concept in mind, a novel distribution of zirconia implants was suggested for the support of
maxillary and mandibular overdentures. The proposed design is expected to improve the biomechanics of zirconia implants and reduce the prosthodontic maintenance events of implant overdentures.

Thus, the aim of this study was to evaluate the outcome of one-piece zirconia implants and compare it with similar design implants made of titanium, when these implants were used for the support and retention of overdentures, in the context of a novel protocol for implant distribution.

**PART I: DIFFERENT IMPLANT MATERIALS**

**Implant Materials**

The physical and chemical properties of the implant material have been reported to influence the clinical outcome (Smith, 1993). These properties involve the micro-architecture of the implant, including surface composition and characteristics as well as design factors. Requirements for successful long-term implants include biocompatibility, toughness, strength, corrosion, wear and fracture resistance (Parr et al., 1985; Smith, 1993). Materials used for the fabrication of dental implants can be categorized according to their chemical composition or the biological response they elicit when implanted. From a chemical point of view, dental implants could be made from metals, ceramics or polymers (Table 1.1) (Sykaras et al., 2000). According to the biodynamic activity, implant materials may be biotolerant, bioinert or bioactive. Biotolerant materials become surrounded by a fibrous layer when implanted into living tissues. Bioinert and bioactive materials are osteoconductive, allowing bone growth on their surfaces. Bioinert materials allow close apposition of bone on their surface, leading to what is known as contact osteogenesis. Bioactive materials allow the formation of new bone onto their surfaces (bonding osteogenesis) (Sykaras et al., 2000).

Commercially pure titanium and its alloys are the most attractive metallic materials for the fabrication of endosseous dental implants (Niinomi, 1998). Numerous investigations have demonstrated the reliability of this material for both mid-and long-term usage (Adell et al., 1990; Jemt et al., 1996). Occasionally, various metals and metal alloys involving gold, stainless steel, and cobalt chromium have been used. However, adverse tissue reactions and a
low success rate undermined their long-term clinical application and made these materials obsolete within the oral implant industry (Wataha, 1996; Sykaras et al., 2000).

Stainless steel, particularly grade 316L (18% chromium, 12% nickel, 2% molybdenum, and 0.03% carbon) continues to be used as a material for bone plates and screws. Despite the fact that this alloy is stronger, cheaper, and easier to machine, its corrosion properties are inferior to those of titanium. For this reason, it has not been approved as a dental implant material (McCracken, 1999).

Cobalt-based alloys have been used in dentistry for decades to make cast partial denture frameworks, and base plates in complete dentures, and have been employed as an implant material. According to the American Dental Association Specification, these alloys should contain a minimum of 85% by weight chromium, cobalt and nickel. Cobalt generally makes up 60% of the alloy by weight. Chromium content has an upper limit of 30% added mainly for mechanical reasons, confers passivity to the alloy, and is responsible for its high resistance to corrosion. Nickel decreases hardness, modulus of elasticity and fusion temperature. These alloys may also contain other metals such as molybdenum, as well as trace amounts of iron, magnesium, silicon and carbon. These alloys cast well and have sufficient strength to withstand occlusal forces; however, well-documented reports about their allergic and carcinogenic potential have led to their limited usage as an implant material (Arvidson et al., 1986; McCracken, 1999).

A variety of ultrahigh molecular weight polymers have also been used as dental implant materials, in the hope that their flexibility would mimic the microenvironment of the periodontal ligament (Meijer et al., 1995; Carvalho et al., 1997; Glantz, 1998). Furthermore, polymers could be easily fabricated into the desired shape. However, inferior mechanical properties, lack of adhesion to living tissues, adverse immunological reaction (Kawahara, 1983; Lemons, 1990) and lack of evidence that flexible implants transfer stress more favorably to bone compared to rigid implants (Meijer et al., 1997) have limited the application of these materials.
<table>
<thead>
<tr>
<th>Implant material</th>
<th>Common name or abbreviation</th>
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<td><strong>I. Metals</strong></td>
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<td>Titanium</td>
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<td>Titanium Alloys</td>
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<td>- Ti-15 Zr-4Nb-2Ta-0.2Pd</td>
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<td>- Ti-29Nb-13Ta-4.6Zr</td>
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<td>Stainless Steel</td>
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<td><strong>II. Ceramics</strong></td>
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<td>Hydroxyapatite</td>
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<td><strong>III. Polymers</strong></td>
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</tr>
<tr>
<td>Polymethylmethacrylate</td>
<td>PMMA</td>
</tr>
<tr>
<td>Polytetrafluoroethylene</td>
<td>PTFE</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>PE</td>
</tr>
<tr>
<td>Polysulfone</td>
<td>PSF</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>PU</td>
</tr>
<tr>
<td>Polyeetheretherketone</td>
<td></td>
</tr>
</tbody>
</table>

Adopted from Williams 1981; Lemons 1990; Craig 1993; Sagomonyants et al., 2007

**Titanium and its alloys**

*Physical and mechanical properties of titanium and its alloys*

It was not until the 1960s that titanium alloys were used as surgical implant materials. Since then, the use of titanium alloys in surgery has been growing steadily (González & Mirza-Rosca, 1999). According to the American Society for Testing and Materials (ASTM), there are six distinct types of titanium available as implant biomaterials. Amongst these six materials, there are four grades of commercially pure titanium (CpTi) and two titanium (Ti) alloys. The mechanical and physical properties of CpTi are different and are related chiefly to the oxygen residuals in the metal (Table 1.2). The two alloys are Ti-6Al-4V and Ti-6Al-4V extra low interstitial (ELI). The commercially pure titanium materials are commercially pure...
grade I, grade II, grade III and grade IV titanium. Commercially pure titanium is also referred to as unalloyed titanium, and usually contains some trace elements of carbon, oxygen, nitrogen and iron. These trace elements markedly improve the mechanical properties of pure titanium (McCracken, 1999).

Titanium alloys of interest to dentistry exist in three structural forms: alpha (α), beta (β), and alpha-beta. These different phases originate when pure titanium is heated and mixed with elements such as aluminum and vanadium in certain concentrations, and then cooled. Aluminum is an alpha-phase stabilizer and increases the strength of the alloy and decreases its weight. On the other hand, vanadium is a beta-phase stabilizer. Allotropic transformation of pure titanium (Ti) from α to β phase occurs at 882°C (González & Mirza-Rosca, 1999). With the addition of aluminum or vanadium to titanium the α-to-β transformation temperature changes to a range of temperatures. Depending upon the composition and heat treatment, both the alpha and beta forms may exist (Parr et al., 1985; McCracken, 1999).

The alpha-beta combination alloy is the most commonly used for the fabrication of dental implants. This alloy consists of 6% aluminum and 4% vanadium (Ti-6Al-4V). Heat treatment of these alloys improves their strength, resulting in favorable mechanical and physical properties that make them excellent implant materials. They have a relatively low density, and are strong and highly resistant to fatigue and corrosion. Although they are stiffer than bone, their modulus of elasticity is closer to the bone than any other implant material with the exception of pure titanium (Niinomi, 1998). This lower modulus of elasticity is desirable, as it results in a more favorable stress distribution at the bone-implant interface (Bidez & Misch, 1992).

Recently, Vanadium free α + β alloys such as Ti-6Al-7Nb and Ti-5Al-2.5Fe have been developed as implant materials because of toxicity concerns with vanadium. Furthermore, vanadium- and aluminum-free titanium alloys composed of non-toxic elements like Nb, Ta, Zr and Pd with lower modulus of elasticity are being developed mainly in the USA. They are mainly β alloys that are more biocompatible compared to α + β alloys because of their lower modulus of elasticity, which is slightly closer to that of bone resulting in a more favorable biomechanical environment. The modulus of elasticity of recently developed β-phase alloys is between 55 to 85 GPa, which is much lower than that of α and α + β alloys, yet still greater than that of bone with a value ranging between 17 and 28 GPa. These alloys are also capable of attaining higher strength and toughness compared to α + β alloys (Niinomi, 1998).
Table 1.2 Mechanical properties of commercially pure titanium and its alloys

<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus (GPa)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>Yield Strength (MPa)</th>
<th>Elongation (%)</th>
<th>Density (g/cc)</th>
<th>Type of alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cp Ti grade I</td>
<td>102</td>
<td>240</td>
<td>170</td>
<td>24</td>
<td>4.5</td>
<td>α</td>
</tr>
<tr>
<td>Cp Ti grade II</td>
<td>102</td>
<td>345</td>
<td>275</td>
<td>20</td>
<td>4.5</td>
<td>α</td>
</tr>
<tr>
<td>Cp Ti grade III</td>
<td>102</td>
<td>450</td>
<td>380</td>
<td>18</td>
<td>4.5</td>
<td>α</td>
</tr>
<tr>
<td>Cp Ti grade IV</td>
<td>104</td>
<td>550</td>
<td>483</td>
<td>15</td>
<td>4.5</td>
<td>α</td>
</tr>
<tr>
<td>Ti-6Al-4V ELI</td>
<td>113</td>
<td>860</td>
<td>795</td>
<td>10</td>
<td>4.4</td>
<td>α + β</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>113</td>
<td>930</td>
<td>860</td>
<td>10</td>
<td>4.4</td>
<td>α + β</td>
</tr>
<tr>
<td>Ti-6Al-7Nb</td>
<td>114</td>
<td>900-1050</td>
<td>880-950</td>
<td>8-15</td>
<td>4.4</td>
<td>α + β</td>
</tr>
<tr>
<td>Ti-5Al-2.5Fe</td>
<td>112</td>
<td>1020</td>
<td>895</td>
<td>15</td>
<td>4.4</td>
<td>α + β</td>
</tr>
<tr>
<td>Ti-15Zr-4Nb-2Ta-0.2Pd</td>
<td>94-99</td>
<td>715-919</td>
<td>693-806</td>
<td>18-28</td>
<td>4.4</td>
<td>α + β</td>
</tr>
<tr>
<td>Ti-29Nb-13Ta-4.6Zr</td>
<td>80</td>
<td>911</td>
<td>864</td>
<td>13.2</td>
<td>4.4</td>
<td>β</td>
</tr>
</tbody>
</table>

Adopted from Lemons 1990; Craig 1993; Wataha 1996; McCracken 1999.

Titanium sensitivity associated with dental implants

Recently there have been some concerns that titanium might evoke an unwelcome host reaction, but little evidence is available in the literature and tentative judgments are only based on case series and isolated clinical reports. A possible association between surface corrosion of titanium on one hand, and hypersensitivity reactions on the other hand has been discussed in the literature (Flatebø et al., 2006; Sicilia et al., 2008; Chaturvedi, 2009; Siddiqi et al., 2011; Javed et al., 2013). Following skin or mucosal contacts, metal ions will be released from implants, which then form complexes with native proteins and act as allergens causing hypersensitivity reactions (Hallab et al., 2001). An increased concentration of titanium has been detected in the peri-implant tissues, regional nodes and pulmonary tissues in animal models with failed implants (Frisken et al., 2002). Furthermore, a somewhat higher blood concentration of titanium has been described in patients with failed loose hip prostheses (Jacobs et al., 1991; Witt & Swann, 1991). However, it is worth noting that the clinical relevance of these findings is not yet clear.

Allergy to titanium in the medical literature has been described in the form of urticaria, pruritus of the skin or mucosa, atopic dermatitis (Tamai et al., 2001), impaired healing of fractures (Thomas et al., 2006), pain, necrosis and weakening of orthopedic implants (Haug, 1996). Non-specific immune suppression or overaggressive immune responses have also been
reported as different forms of allergy to titanium, particularly with sensitive patients. However, whether the findings of these studies can be extrapolated to the oral cavity and dental implants is debatable (Sicilia et al., 2008). One reason would be the smaller intraosseous contact surface of dental implants compared to orthopedic implants, considering that bone has a very low reactivity potential (Schramm & Pitto, 2000). On the other hand, the decreased permeability of mucosa compared to skin implies that the antigen concentration has to be 5-12 times greater to elicit the same response. Furthermore, the salivary glycoprotein layer formed on implant surfaces once implanted into the oral cavity may act as a protective barrier (Bass et al., 1993).

In the dental literature, titanium hypersensitivity has been described in the form of facial eczema, dermatitis, rashes, non-keratinized edematous hyperplastic gingiva and rapid implant exfoliation, which could not be attributed to infection, impaired healing or overload (Mitchell et al., 1990; du Preez et al., 2007; Müller & Valentine-Thon, 2007; Egusa et al., 2008; Sicilia et al., 2008). A recent review suggested that the incidence of allergic reactions to titanium dental implants may be under-reported as a possible etiological factor in implant failure, due to lack of recognition, and infrequent or ambiguous clinical presentations (Siddiqi et al., 2011).

In summary, the clinical relevance of allergic reactions in patients with titanium dental implants remains debatable. The results of two recent reviews on the topic reported different conclusions (Javed et al., 2013; Siddiqi et al., 2011). In the first review, it was concluded that the significance of titanium as a cause of allergic reactions in patients with dental implants remains unproven (Javed et al., 2013). On the other hand, the results of the other review indicated that titanium could induce hypersensitivity in susceptible patients, and might play a critical role in causing implant failure (Siddiqi et al., 2011). Thus, it would be prudent, until research proves otherwise, to use implants of alternative materials in patients with proven allergy to titanium.

**Ceramics**

*Ceramics as dental implant coatings*

Ceramics were first introduced to implant dentistry in the form of coatings onto metal-based endosseous implants in an attempt to improve the strength of the implant-bone bond and thus osseointegration. Over the last 15 years, various forms of ceramic coatings have been
used on dental implants (Table 1.3). This involved both the bioactive ceramics such as calcium phosphates and bioglasses, and inert ceramics including aluminum oxide and zirconium oxide. Coatings can be dense or porous, with a thickness ranging from 1-100 μm, depending on the coating method that is employed. Different methods to coat metal implants comprise plasma spraying, sputter-deposition, sol-gel coating, electrophoretic deposition or biomimetic precipitation (Lacefield, 1998). Bioactive ceramics have been shown to release calcium phosphate ions around the implants, resulting in enhanced bone apposition compared with the more inert ceramic and metallic surfaces (De Groot et al., 1994; Lacefield, 1998; Morris et al., 2000; Barrere et al., 2003; Le Guéhennec et al., 2007). Amongst the most popular calcium phosphate coating materials are plasma-sprayed dense hydroxyapatite and fluoroapatite. These coatings, depending upon deposition conditions, contain regions which are partially amorphous; at the same time they also retain regions that are highly crystalline. This appears to be important for eliciting specific biological response to these materials. Furthermore, the dense coatings are characterized by higher strengths and lower solubility. Inert ceramic materials are rarely used as coatings, because they do not appear to be as osteoconductive as the more bioactive calcium phosphate materials. Despite a clinical success of 97.8% reported for HA-coated implants, concerns about degradation and debonding of these coatings have been raised (Wheeler, 1996; Yu-Liang et al., 1999; Tinsley et al., 2001).

<table>
<thead>
<tr>
<th>Material</th>
<th>Chemical composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydroxyapatite (HA)</td>
<td>Ca₁₀(PO₄)₆(OH)₂</td>
</tr>
<tr>
<td>Tricalcium phosphate (TCP)</td>
<td>α, β, Ca₃(PO₄)₂</td>
</tr>
<tr>
<td>Fluorapatite (FA)</td>
<td>Ca₁₀(PO₄)₆F₂</td>
</tr>
<tr>
<td>Tetracalcium phosphate</td>
<td>Ca₄P₂O₉</td>
</tr>
<tr>
<td>Calcium pyrophosphate</td>
<td>Ca₄P₂O₇</td>
</tr>
<tr>
<td>Brushite</td>
<td>CaHPO₄, CaHPO₄.2H₂O</td>
</tr>
<tr>
<td>Bioglasses</td>
<td>SiO₂-CaO-Na₂O-P₂O₅-MgO, etc.</td>
</tr>
<tr>
<td>Aluminum oxide</td>
<td>Al₂O₃</td>
</tr>
<tr>
<td>Zirconium oxide</td>
<td>ZrO₂</td>
</tr>
</tbody>
</table>

Adopted from Lacefield 1998

Ceramics as dental implant materials

With the development of biomaterial science and industrial technology, ceramics with improved mechanical properties were developed and suggested as a possible substrate for bulk implant materials. Pioneer attempts to use ceramics as an alternative implant material
involved the use of aluminum oxide, both in the form of single crystalline sapphire and polycrystalline alumina (Zetterqvist et al., 1991). However, the inferior mechanical properties and reduced survival rates of these systems compared to titanium implants led to their withdrawal from the market. Despite the fear that alumina implants may be susceptible to fracture due to their brittleness, low tensile strength, long-term ageing, it was only in one study that implant fracture was stated as the cause of the implant failure (Fartash & Arvidson, 1997). According to Kohal and colleagues (2008), the main reason for the withdrawal of some of the alumina implant systems from the market remained unclear. They assumed that the fear of dentists that alumina implants were prone to fracture might have played a crucial role.

Zirconia

With the introduction of zirconia, particularly the yttrium-stabilized tetragonal polycrystalline zirconia (Y-TZP), interest in ceramics as a material of choice was renewed. Y-TZP was first introduced in the 1980s and was extensively used in orthopedic surgery as a material for ball heads in total hip replacement (Christel et al., 1988). Y-TZP was first used in dentistry as a material for frameworks in all-ceramic fixed partial denture framework and as an abutment for all-ceramic restorations (Raigrodski, 2004).

Zirconia holds a unique place amongst oxide ceramics due to its excellent mechanical properties (Black & Hastings, 1998). At ambient pressure, unalloyed zirconia can assume three crystallographic forms, depending on the temperature. At room temperature and upon heating up to 1170°C, the structure is monoclinic. It assumes a tetragonal form between 1170 and 2370°C, and cubic structure above 2370°C and up to the melting point. Alloying pure zirconia with stabilizing oxides such as CaO, MgO, Y2O3 or CeO2 allows the retention of the metastable tetragonal structure at room temperature. Dental procedures such as grinding or sandblasting can trigger the tetragonal to monoclinic transformation (Piconi & Maccauro, 1999). This transformation is accompanied by a substantial increase in volume (≈4.5%) that induces compressive stresses, thereby closing the crack tip and enhancing resistance to further propagation. This characteristic, known as transformation toughening, increases fracture strength and fracture toughness of Y-TZP ceramics compared with other dental ceramics (Garvie et al., 1975).

Types of zirconia used in dentistry
Despite the plethora of the zirconia-containing ceramic systems available on the market today, to date only three have been used in dentistry. These are yttrium-stabilized tetragonal zirconia polycrystals (3Y-TZP), magnesia-partially-stabilized zirconia (Mg-PSZ) and zirconia-toughened alumina (ZTA).

**Yttrium-stabilized tetragonal zirconia polycrystals (3Y-TZP)**

The microstructure of 3Y-TZP ceramics for dental applications consists of up to 98% small equiaxed tetragonal grains (0.2 µm-0.5 µm), sometimes combined with a small fraction of the cubic phase, and 3 mol % yttria (Y₂O₃) as a stabilizer. The mechanical properties of 3Y-TZP depend on its grain size, which is dictated by the sintering temperature (Ruiz & Readey, 1996). Above a critical grain size, 3Y-TZP is less stable and more susceptible to spontaneous tetragonal to monoclinic transformation, whereas smaller grain sizes (<1µm) are associated with a lower transformation rate (Heuer et al., 1982). Moreover, the transformation is not possible below a certain grain size (0.2 µm), which results in reduced fracture toughness (Cottom & Mayo, 1996). Higher sintering temperatures and longer sintering times lead to larger grain sizes. The initial application of 3Y-TZP in the field of orthopedics showed significant success due to its good mechanical properties and biocompatibility. However, its use has been reduced by more than 90%, mostly due to a series of failures of roughly 400 femoral heads in a very short period. To account for such failures, an accelerated ageing process due to processing techniques was suggested (Chevalier, 2006). Consequently, the necessity of assessing the ageing sensitivity of different products associated with various processing techniques was stressed.

In dentistry, 3Y-TZP is used for the fabrication of single crown restorations, fixed partial dentures, implant abutments, and orthodontic brackets, and is a substitute for metal frameworks. Recently, 3Y-TZP has been used as a substrate for the manufacture of single piece endosseous oral implants. Prosthetic restorations with 3Y-TZP are obtained by soft machining of presintered blanks followed by sintering at high temperature, or by hard machining of fully sintered blocks (Filser et al., 2003). Soft machining of 3Y-TZP utilizes materials with final sintering temperatures varying between 1350 and 1550°C, depending on the manufacturer (Denry & Kelly, 2008; Volpato et al., 2011). This fairly wide range of sintering temperatures is therefore likely to have an influence on the grain size and later the phase stability of 3Y-TZP for dental applications. The soft machining of zirconia blanks prevents the stress-induced transformation from tetragonal to monoclinic, and leads to a final sintered surface virtually free of monoclinic phase, unless grinding adjustments are needed or
sandblasting is performed. On the other hand, hard machining of fully sintered zirconia blocks has been shown to result in a significant amount of monoclinic phase with subsequent surface micro-cracking and higher susceptibility to low temperature degradation (Volpato et al., 2011). Recently, ceramic blocks known as TZP-A have been produced by introducing small amounts of alumina to 3Y-TZP. The added alumina improves the durability and stability under high temperatures and humid environments. However, this has been at the expense of reduced translucency of ceramic blocks (Volpato et al., 2011).

Glass-infiltrated zirconia-toughened alumina (ZTA)

Ceramics based on zirconia are combined with a matrix of alumina (Al₂O₃) to advantageously utilize the stress induced transformation capability of zirconia and produce a structure known as ZTA (alumina reinforced with zirconia grains). The material is developed by adding 33 vol.% of 12 mol% ceria-stabilized zirconia (12Ce-TZP) to In-Ceram Alumina (Guazzato et al., 2004a). In-Ceram Zirconia can be processed by either slip-casting or soft machining (Denry & Kelly 2008). The slip casting technique is associated with very limited amounts of shrinkage upon sintering. However, the great amount of porosity incorporated (8-11%) during the procedure results in lower mechanical properties of this material compared to 3Y-TZP dental ceramics (Guazzato et al., 2003; 2004b). On the other hand, the soft machining of the presintered Y-TZP blocks results in higher mechanical properties, creating tougher prostheses, but with sintering contractions of around 25% (Denry & Kelly, 2008).

Magnesia partially stabilized zirconia (Mg-PSZ)

The microstructure of Mg-PSZ consists of tetragonal precipitates within a cubic zirconia matrix stabilized by 8 to 10 mol% of magnesium oxide. Due to difficulty in obtaining free silica Mg-PSZ precursors (SiO₂), magnesium silicates can be formed, which reduce the Mg content, promote the tetragonal to monoclinic transformation, and thus diminish the mechanical properties of the material (Denry & Kelly, 2008).

Low temperature degradation (LTD)

An important issue concerning zirconia ceramics is their sensitivity to low temperature degradation (Chevalier et al., 2011). Ageing occurs by a slow surface transformation of the metastable tetragonal crystals to the stable monoclinic structure in the presence of water or water vapor. A certain degree of surface tetragonal-monoclinic transformation can actually improve the mechanical properties of Y-TZP due to the creation of a compressive monoclinic
layer on the surface of ceramic. However, a narrow range exists between improvement and destruction of mechanical properties, as further ageing results in property deterioration (Lawson, 1995). Transformation starts first in isolated grains on the surface by a stress corrosion mechanism. The transformation of one grain leads to a volume increase, thereby stressing the neighboring grains and generating micro-cracking which enables further water penetration and crack propagation (Chevalier 2006). Experimental observations have shown that the degradation proceeds most rapidly at temperatures of 200-300°C and is time-dependent.

The ageing process depends on several microstructure features such as porosity, residual stresses, grain size and stabilizer content of the processed material. A decrease in grain size and an increase in stabilizer content were found to retard the transformation process. The critical grain size reported in the literature ranges from 0.2 to 1 µm depending on Y₂O₃ content. A grain size larger than 1 µm was reported to exhibit a large amount of tetragonal-monoclinic transformation, together with a remarkable decrease in strength, whereas grains of < 0.4 µm showed no significant change of phase content or strength. At a grain size below 0.2 µm, no tetragonal-monoclinic transformation can occur, resulting in reduction in fracture toughness. Watanabe et al. (1984) estimated that the critical grain size for tetragonal phase retention depends on Y₂O₃ content, and suggested that the critical grain size increases from 0.2 to 0.6 µm as the Y₂O₃ content increases from 2 to 5 mol%.

The consequences of the aging process on the performance of zirconia implants include roughening of the surface, increased wear, and microcracking with the resultant decrease in mechanical properties in the medium-and long-term. Another possible consequence is the premature failure of the material when the microcracked and damaged zone reaches the critical size for slow crack growth to proceed. It was claimed that the ageing process was limited and not critical in the in-vivo situation until year 2001, when roughly 400 femoral heads failed in a very short period. On investigating the reasons of failure of these heads, Chevalier (2006) found it to be associated with an accelerated ageing related to the changes in the processing techniques used. The latter led to changes in the microstructure of material. Thus the author emphasized the importance of accurate processing techniques in avoiding accelerated ageing as compared to normal ageing processes. In accordance, clinical retrieval studies seem to confirm the strong variability of zirconia heads with regard to LTD resistance, supporting the claim that the inaccuracy in processing techniques was the major causative factor that affects LTD resistance. However, the need for more advanced studies on the
correlation between microstructure and LTD resistance in-vivo is still warranted. An in-vitro simulation investigating the effect of ageing on zirconium oxide used for oral rehabilitation found that although ageing reduces the mechanical features of zirconia, the decrease occurs within clinically acceptable values (Att et al., 2007). In accordance, the findings of a recent in-vitro study showed that dental procedures did not significantly change the bulk properties of zirconia (flexural strength and yttria composition), indicating a longer-term in-vivo function without biomechanical fracture (Alghazzawi et al., 2012).

Attempts to minimize the LTD of 3Y-TZP systems include the addition of small amounts of silica (Gremillard et al., 2002), the use of yttria coated rather than co-precipitated powder, reduction of the particle size (Piconi et al., 1998), increase of the stabilizer content, or even the formation of composites with aluminum oxide (Al₂O₃) (Lee et al., 2000). A composite material processed with 80% tetragonal zirconia polycrystals (ZrO₂-TZP) and 20% alumina (Al₂O₃) is reported to have outstanding mechanical and tribological properties. The addition of alumina to zirconia clearly hinders ageing, or at least reduces drastically its kinetics, as it prevents the relaxation of tetragonal zirconia network under stress, which is responsible for the ageing process (Lee et al., 2000).

Osseointegration of Y-TZP dental implants under different loading conditions in animal models

Animal studies demonstrated bone integration of threaded zirconia implants comparable to that of titanium after insertion in different animal models and sites and under different loading conditions. In those studies, the mean bone-implant contact was above 60%, indicating successful osseointegration. Akagawa et al. (1993) were the first to evaluate loaded versus unloaded zirconia oral implants in beagle dogs. They found direct bone apposition to the implants in both groups with bone-to-implant contact ratio of 81.9 and 69.8% for the unloaded and loaded groups respectively. In a follow-up study, the same authors evaluated osseointegration of Y-TZP implants subjected to different loading modalities in monkeys (Akagawa et al., 1998). No significant differences were detected in clinical parameters or osseointegration, nor were there any mechanical problems encountered between different loading groups. The different loading groups were a single implant, two connected implants and implant-tooth-supported restorations. However, in the previously mentioned studies, no titanium control group was included for comparison. In a split mouth design, Kohal et al. (2004) compared osseointegration and peri-implant soft tissue dimensions between loaded titanium and zirconia implants in a primate model and found no statistical difference between
the two materials. Several other animal investigations showed that zirconia implants undergo osseointegration similar to (Dubruille et al., 1999; Scarano et al., 2003; Depprich et al., 2008; Hoffmann et al., 2008; Gahlert et al., 2012a) or even better (Schultze-Mosgau et al., 2000) than that of titanium implants.

A number of studies investigated the influence of surface microtopography on the osseointegration of zirconia implants. In a rabbit model, Sennerby et al. (2005) and Rocchietta et al. (2009) analyzed histologically and biomechanically the bone tissue response to Y-TZP with different surface topographies and used oxidized titanium implants as controls. The removal torque values were significantly higher for surface modified zirconia and titanium implants compared to machined-surface implants, with no significant difference regarding bone-to-implant contact between the two different materials. In accordance with the previous results, Gahlert et al. (2007) concluded that sandblasted roughened ZrO₂ implants enhanced the bone stability and achieved a higher stability in the bone compared to machined surface implants. Schliephake et al. (2010) compared the peri-implant bone formation and mechanical stability of surface modified zirconia implants with sandblasted and acid-etched titanium implants and found similar degrees of bone implant contact and bone volume density for all the implants, despite the fact that the titanium surface was significantly rougher than the tested zirconia surfaces. However, titanium implants were found to have a higher resistance removal torque probably due to the difference in the surface roughness.

A cell culture study by Bächle et al. (2007) found cell attachment and proliferation of osteoblast-like cells on Y-TZP disks of differently treated surfaces were comparable to those of a sandblasted/acid-etched titanium surface. In contrast, another study showed that modified zirconia surfaces mediate more pronounced adhesion, proliferation and differentiation of osteoblasts compared with titanium (Hempel et al., 2010). Another study investigated the osteoblast cell adhesion on laser modified Y-TZP surfaces and found higher wettability on modified surfaces compared to smooth untreated specimens. The authors attributed this to the enhancement of surface energy caused by laser treatment (Hao et al., 2005). Coating the surface of Y-TZP implants with bioactive glass was also reported to accelerate bone healing and improve the osseointegration process (Aldini et al., 2004).

Numerous other in-vitro studies investigated the influence of different surface modifications on osteoblasts and fibroblasts cell adhesion to zirconia implants, concluding
that the surface roughness of zirconia improve initial bone healing and resistance to removal torque (Ferguson et al., 2008; Payer et al., 2010; Zinelis et al., 2010; Park et al., 2012).

Zirconia and peri-implant soft tissues

Recently, Mellinghoff (2010) presented a review of literature on peri-implant soft tissue around zirconia implants, comparing the results with the experience from his own practice. The findings showed that zirconia implants and abutments provide a very good peri-implant soft tissue interface that achieves an irritation-free attachment. Various \textit{in-vivo} and \textit{in-vitro} investigations of soft tissue response around zirconia revealed comparable (Pae, 2009) or even better healing response, less inflammatory infiltrate and reduced plaque adhesion on zirconium oxide discs compared to conventionally pure titanium (Rimondini et al., 2002; Scarano et al., 2004; Degidi et al., 2006, Größner-Schreiber et al., 2006).

In a human \textit{in-vivo} study, Scarano et al. (2004) quantified the percentage of surface coverage of titanium and zirconium oxide discs by bacteria and found a statistically significant difference between the two materials. The zirconium oxide surfaces showed a significant reduction in bacterial adhesion when compared to the titanium specimens. This could positively affect the health of peri-implant soft tissues as suggested by the authors. Another \textit{in-vivo} human study compared vascular endothelial growth factor (VEGF) and nitrous oxide synthase (NOS) expression, inflammatory infiltrate, and microvessel density (MVD) in peri-implant soft tissue of titanium and zirconium healing caps. The results revealed higher values of VEGF, NOS, MVD and more extension of inflammatory infiltrate with a subsequently higher rate of inflammation-associated process in the titanium specimens compared to that of zirconium oxide specimens (Degidi et al., 2006). Moreover, an \textit{in-vivo} animal study analyzed soft tissue responses to implant abutments made of titanium, ZrO$_2$, Ti and Au-Pt alloy and found no difference in the soft tissue dimensions between Ti and ZrO$_2$ abutments at two and five months of healing; however, a significant difference was found between the two materials and Au-Pt alloy (Welander et al., 2008). In accordance, Kohal et al. (2004) found no difference in soft tissue integration around rough titanium and zirconia implants in a monkey model.

In an \textit{in-vitro} and \textit{in-vivo} study, Rimondini et al. (2002) compared oral bacterial colonization on the surfaces of disks fabricated from machined grade 2 Ti and Y-TZP. Y-TZP was found to accumulate fewer bacteria than Ti and was suggested to be a promising material for abutment manufacturing. On the other hand, Lima et al. (2008) and Al-Ahmad et al.
(2010) found that Ti and ZrO₂ surfaces displayed similar biological properties in terms of protein adsorption, biofilm composition and bacterial adherence.

The attachment, growth behavior and the genetic effect of human gingival fibroblasts (HGF) cultured on titanium and different zirconia surfaces (smooth and grooved) were investigated. HGFs showed comparable biological responses to both grooved zirconia ceramic and pure titanium surfaces (Pae et al., 2009).

Clinical studies, case reports and case series on zirconia implants

A recent study analyzed the survival and success of zirconia dental implants based on the available clinical data from case reports, prospective and retrospective clinical studies, and randomized multicenter studies (Depprich et al., 2012). All of these studies except one (Nevins et al., 2011) reported on the use of one-piece zirconia implants. The post-observation period ranged from one to five years with a reported survival rate of 74-98% after 12-56 months and success rates between 79.6-91.6% after 6-12 months of prosthetic restoration. Nevertheless, the authors highlighted that there is a low-level of evidence to support the use of zirconia dental implants due to the limited period of observation and number of participants in the included studies. Furthermore, they stressed the urgent need for well conducted long-term randomized controlled trials to establish an evidence-based use of zirconia implants as an alternative to titanium implants (Depprich et al., 2012).

A number of case reports demonstrated the use of one-piece zirconia implants with roughened surface for the replacement of missing single as well as multi-rooted teeth in either jaw with excellent aesthetic and functional outcomes after a follow-up period ranging from 1 to 3 years (Kohal & Klaus, 2004; Oliva et al., 2008a,b,c; Pirker & Kocher, 2008, 2011; Aydin et al., 2010; Piker et al., 2011). In the same context, the results of a prospective case series on the outcome of immediately provisionalized single-piece zirconia implants restoring single tooth gaps in the maxilla and mandible revealed comparable results to immediately restored titanium implants after 24 months of clinical function (Payer et al., 2012). Nevins et al. (2011) reported the only case in which two-piece zirconia implants with platform switching was used in a human model. Radiographic observations revealed excellent vertical bone height located coronal to implant abutment junction, eliminating the significance of the microgap.
The success rate of one-piece zirconia implants with different surface treatments was evaluated in two prospective studies. The results revealed overall success rates of 92-95% over follow-up periods ranging from 2.5 to 5 years with excellent aesthetic and functional results. No mechanical complications were encountered and it was suggested that zirconia implants might be a viable alternative to titanium implants for tooth replacement (Pirker & Kocher, 2009; Oliva et al., 2010a).

On the other hand, the findings of a cohort prospective study evaluating the clinical and radiographic outcome of a one-piece zirconia oral implant for single tooth replacement could not confirm the previous results. The one-year follow-up showed a comparable survival rate for the immediately loaded ceramic and titanium implants. However, the increased radiographic bone loss of more than 2mm around ceramic implants precluded its recommendation for clinical use (Kohal et al., 2012).

A multicentre randomized clinical trial which evaluated immediate occlusal and non-occlusal loading of single zirconia implants could not provide a conclusive answer. Alternatively, the conclusion of the study was that immediately loaded zirconia implants placed in post-extractive sites had higher failure rates than implants placed in healed sites (Cannizzaro et al., 2010).

The use of zirconia as restorative components has been widely cited in the literature (Raigrodski, 2004; Manicone et al., 2007); however, Y-TZP has yet to be established as the material of choice for endosseous oral implants. Given the brittle nature of ceramics, optimizing the implant distribution is a prerequisite for improving the biomechanical environment and ensuring the mechanical integrity of implants during the functional loading. An in-vitro study evaluating the mechanical properties of zirconia implants revealed fracture strength values ranging from 512.9 N for the non-loaded group versus 410.7 N after artificial loading (Kohal et al., 2006). In another study, the influence of crown preparation on the reliability of one-piece zirconia implants was evaluated. The authors found that the fracture strength of zirconia implants without preparation was 1023.3 N, and with full crown preparation was 1111.7 N (Silva et al., 2009). However, in another study, it was concluded that preparation of the implant heads had a significant negative influence on implant fracture strength, though in both situations the mean fracture strength values were within the limits of clinical acceptance (Andreiotelli & Kohal, 2009).
PART II: IMPLANT OVERDENTURE DESIGNS

Prosthodontic design plays an important role in the treatment outcome of implant overdentures and is different in the mandible compared to the maxilla (Desjardins, 1992; Williams et al., 2001), due to differences in residual ridge structure, anatomy, biomechanics, phonetics and aesthetic requirements (Williams et al., 2001; Henry, 2002). Nevertheless, the ultimate requirement for any design would be its ability to preserve the remaining structures, to function with minimal stresses imparted to implants, to satisfy the patients’ demands and to allow the longevity of the prostheses. In the absence of any consensus, there appears to be a wide variation with regard to the recommended implant number, their distribution and attachment system selected for either maxillary or mandibular overdentures (Batenburg et al., 1998a; Chan et al., 1998; Sadowsky, 2007).

Implant number & distribution in mandible

A great variation in the number and distribution of implants used to retain mandibular overdentures exists in the literature (Batenburg et al., 1998a,b; Visser et al., 2005; Walton et al., 2009). Prospective and retrospective studies on two versus four interforaminal implant overdentures revealed comparable survival rates, clinical outcomes and patients’ satisfaction levels amongst both groups (Batenburg et al., 1998b; Wismeijer et al., 1999; Mau et al., 2003; Visser et al., 2005). A systematic review of implant survival rates in relation to prostheses type revealed insignificant difference between mandibular overdenture designs with one, two, four or more implants. The authors reported pooled implant survival estimates of 96% and 95% at 5- and 10-year follow-up periods, respectively (Bryant et al., 2007). Meijer et al. (2009) found no difference in patients’ satisfaction with mandibular overdenture design on two or four implants during an evaluation period of 10 years. The amount of aftercare and cost analysis represents other factors that can influence the choice of the number of implants. In an eight-year randomized controlled trial, Stoker et al. (2007) compared aftercare and cost-analysis for three types of mandibular implant-retained overdentures and found the total cost to be significantly higher for the group with four implants and a triple bar attachment compared to the other two groups with two implants with either a single bar or ball attachment. However, the highest number of prosthodontic aftercare requirements was reported for 2-implant overdentures with ball attachments. The authors concluded that a two-implant bar-retained overdenture might be the most efficient modality in the long-term.
Evidence of biologic success and psychological satisfaction with the two-implant overdenture design led to the consensus that it should be the standard of care, though this statement is now disputed (Feine et al., 2002; Fitzpatrick, 2006). It has also been argued that clinical situations with advanced atrophy, opposing dentate or partially dentate maxilla, high muscle attachments, prominent mylohyoid ridges, and extreme gagging reflex necessitate the use of an increased number of implants (Batenburg et al., 1998a; Mericske-Stern et al., 2000a).

Recently, a number of studies revealed the feasibility of managing mandibular edentulism in elderly patients, using overdentures anchored by single mid-symphysisal implants. Remarkable improvement on oral function and comfort, minimal surgical procedures and complications, simplified imaging procedures and reduced treatment cost are all advantages of this design (Cordioli et al., 1997; Krennmair & Ulm, 2001; Alsabeeha et al., 2009; Walton et al., 2009). However, a long-term observation period is mandatory before recommending a single midline implant to support a mandibular overdenture as an alternative to the two implants for maladaptive denture patients (Alsabeeha et al., 2009; Walton et al., 2009).

The use of mini-implants supported mandibular overdentures as a definitive method for resolving the edentulous predicament is a relatively recent topic with encouraging preliminary results (LaBarre et al., 2008; Morneburg & Pröschel, 2008). Mini-dental implants are indicated in the interforaminal area, in a minimum number of 4 in the cases where jaw morphology does not allow the conventional implant application without surgical interventions. A minimal ridge width of more than 5mm is needed to apply a conventional implant. Mini dental implants with reduced diameters of 1.8 and 2.1mm can be inserted into a ridge width of 3-4mm (Preoteasa et al., 2010).

Data on the use of additional posterior implants for mandibular overdenture support are scant in the literature. Anatomic structures such as the inferior alveolar nerve may restrict the available bone at the prospective implant site (Maló et al., 2007). The posterior regions usually exhibit less favorable bone quality and less bone volume than the anterior regions (Teixeira et al., 1997; Becker et al., 1999). Surgical procedures to overcome these limitations as bone augmentation and inferior alveolar nerve repositioning are invasive, and require more time and cost (Rosenquist, 1992; Felice et al., 2008). Placement of short-length dental implants has been proposed as an alternative option (Neldam & Pinholt, 2012). The treatment outcome of short dental implants has not been clearly reported in the literature and has
produced conflicting results (Neldam & Pinholt, 2012). However, recently, with the development of implant design, surface structure, and improved surgical techniques, short implants have demonstrated the same level of success as longer ones (Maló et al., 2007; Neldam & Pinholt, 2012). A retrospective study, evaluating the overall success rate of short dental implants placed in partially or completely edentulous posterior mandible restored with fixed or removable prostheses, reported success rates as high as 98.9% over an observation period ranging from 1 to 9 years (Maló et al., 2007). Short implants preclude the need for augmentation procedures prior to or in conjunction with implant placement, and reduce the surgical risk of mandibular parasthesia (Grant et al., 2009).

**Implant number & distribution in maxilla**

By far the majority of early and subsequent reports have advocated the use of multiple implants to retain and/or support maxillary overdentures (Chan et al., 1998; Henry, 1998; Eckert & Carr, 2004; Jivari et al., 2006; Sadowsky 2007; Slot et al., 2010). In a systematic review, Sadowsky (2007) concluded that four was the minimum number of implants and recommended six implants in compromised clinical situations. Similarly, a recent meta-analysis study on maxillary implant overdentures reported implant survival rates of 98.2% and 96.3% per year for six and four implants respectively (Slot et al., 2010). Payne et al. (2004) reported a one-year survival rate of 84.6% when three narrow diameter and early loaded (12 weeks) implants were used in the maxilla for the overdenture support. Two implant maxillary overdentures are not recommended as a definite treatment modality but rather as a temporary solution with full palatal coverage because of morpho-anatomic considerations (Mericske-Stern, 1998; Mericske-Stern et al., 2000a).

The resorptive pattern of the maxilla, sinus pneumatization and the presence of nasal cavities often pose a challenge for prosthodontic implant reconstruction, particularly in an atrophic maxilla. A number of different treatment modalities have been developed, with varying results. The most noteworthy approaches include grafting procedures (Listrom & Symington, 1998), sinus lifting (Khoury, 1999), tilted implant placement along sinus wall (Maló et al., 2005), and the use of alternative implant sites other than the edentulous alveolar ridge (Scher, 1994; Aparicio et al., 2006; Machado et al., 2008; Peñarrocha et al., 2009a). Alternative anatomic sites offer reduced morbidity and minimal invasion of the existing structures. Buttress implants (zygomatic and pterygoid implants), mid palatal and nasopalatine implants are examples of such sites (Scher, 1994; Aparicio et al., 2006; Machado et al., 2008; Peñarrocha et al., 2009b). Success rates for these locations are encouraging in the
rehabilitation of completely edentulous cases and compare favorably with the success rate of other anatomic locations in the maxilla (Henry, 1998). Peñarrocha et al. (2012) found a high success rate of implants placed in the anatomic buttresses of the atrophic maxillae (pterygomaxillary, nasopalatine, and zygomatic implants) to rehabilitate patients with combination syndrome.

Traditionally, as a precaution, the nasopalatine canal has been avoided to prevent damage to its neuro-vascular content (Liang et al., 2009). However, a number of studies utilizing nasopalatine implants for replacement of missing maxillary incisors reported encouraging results with implants osseointegration and lack of complications (Rosenquist et al., 1992; Artzi et al., 2000). In these studies, the canal contents were displaced by block graft and maintained (Artzi et al., 2000) or severed (Rosenquist et al., 1992); and in both situations it was reported that there was no loss of sensation and complete soft tissue healing was evident. In corroboration Magennis (1990) reported no altered sensation in a number of patients following dissection of nasopalatine nerve while raising a palatal flap. This could be supported by the fact that this is a densely innervated area with the nasopalatine nerve having only a minor influence (Scher 1994). Scher (1994) reported a case of an uneventful healing of an incisive canal implant used in conjunction with premolar implants following a sinus lift procedure to support and retain a maxillary overdenture. Recently, Peñarrocha et al. (2009a) in a pilot study reported high patients’ satisfaction with their prosthesis when the nasopalatine canal was used as an anatomic buttress for implant placement. The anterior support provided by a nasopalatine implant decreases the bending moment created at the vertical plane when the prosthetic restoration is loaded (Peñarrocha, 2012).

For more than 15 years, palatal implants have been used as temporary skeletal orthodontic anchorage elements. Experimental and clinical studies assessing the anatomic basis for palatal implants showed that the mid-sagittal area of the palate between the first premolars lends sufficient bony support for the implantation of 5-6mm length endosseous implants (Wehrbein et al., 1999; Schlegel, 2002). Machado et al. (2008) reported the successful use of 1 mini-implant in the mid-palatal suture and 2 implants in the canine area in a triangular design to gain support and retention for a maxillary overdenture. Ambard (2009) described the use of palatal implants either in descending premaxilla or mid-palatal suture for adequate retention for maxillary removable interim prostheses.
Successful use of zygomatic implants has been clinically established with a survival rate ranging from 94% to 100% when they are used in combination with at least two standard implants in the anterior maxilla in a semicircular configuration (Ahlgren et al., 2006; Aghabeigi & Bousdras, 2007; Aparicio et al., 2008). The use of zygomatic implants results in reduced overall treatment time when compared to conventional grafting procedures. However, the installation of these implants is technique sensitive, and requires a thorough knowledge of procedure and great surgical skills. There is a risk of orbital injuries, post-operative sinusitis and damage to zygomatico-facialis nerve in association with surgery. Due to the palatal position of implants, a more complex prosthodontic design is needed. Furthermore, oral hygiene measures are difficult with resultant soft tissue complications (Nakai et al., 2003; Ahlgren et al., 2006; Aparicio et al., 2008).

The longevity of implant overdentures was influenced not only by the biological outcome, but also by the prosthodontic maintenance requirements.
PART III: PROSTHODONTIC MAINTENANCE in RELATION TO DIFFERENT IMPLANT OVERDENTURE DESIGNS

Publication status: Published


INTRODUCTION
Rehabilitation of edentulous patients with implant overdentures, irrespective of the opposing dentition or prosthesis, commits them to future prosthodontic maintenance. The key to prosthodontic success of implant overdentures is minimizing the future burden of post-insertion maintenance. Mechanical complications of the attachment systems selected along with mucosal problems are considered to be the most relevant in terms of maintenance requirements encountered (Walton & MacEntee, 1994; Watson et al., 1997; Akça et al., 2010; Çehreli et al., 2010). Differences in maintenance requirements are related to the plethora of overdenture designs with various patrix and matrix components, independent of the implant systems used (Henry, 1998; Bryant et al., 2007; Çehreli et al., 2010). The number of implants, their position, and degree of parallelism influence overdenture design and subjective selection of the attachment system (Slot et al., 2010). These factors are essential in relation to the required mucosal support and palatal coverage from the primary and secondary stress-bearing areas in the case of maxillary overdentures (Finley, 1998; Karabuda et al., 2008). Stable overdenture design is facilitated by implant alignment that limits the micro-movement during function, wear of attachment systems and decreases maintenance requirements (Zitzmann & Marinello, 2000; Watson et al., 2001; Widbom et al., 2005; Krennmair et al., 2008). Connecting bars as opposed to free-standing single ball, stud or magnetic attachment systems have dominated the literature for maxillary overdentures (Palmqvist et al., 1994; Jemt et al., 1996; Ekfeldt et al., 1997; Bergendal & Engquist, 1998; Naert et al., 1998; Widbom et al., 2005; Krennmair et al., 2008). Nevertheless, some authors have reported the use of ball abutments with favourable outcomes. For mandibular overdentures, several authors concluded that with optimized loading conditions, and optimal base extension, the anchorage systems appear to have less of an influence on treatment outcome. However, many authors emphasized that the ball attachments require more frequent postoperative care than bar
attachments to ensure successful long-term outcome (Den Dunnen, 1997; Payne & Solomons, 2000a; Chaffee et al., 2002; Van Kampen et al., 2003; MacEntee et al., 2005; Karabuda et al., 2008) while others do not support this finding (Naert et al., 1999; Gotfredsen & Holm, 2000). A recent systematic review revealed that prosthetic maintenance requirements for implant overdentures on both jaws are comparable and that the type of attachment system has no effect on the prosthetic outcome after 5 years of function (Çehreli et al., 2010). Regardless of the attachment and implant system used prosthetic complications such as wear of retentive components, loosening or breakage of matrices, retightening of fixation screws, fracture of bars and/or bar extensions and denture repair have been reported (Walton & MacEntee, 1994; Davis et al., 1996; Davis & Packer, 1999; Walton et al., 2002; Çehreli et al., 2010). A common ground of consensus is that the maintenance of different attachment designs is usually greatest during the first year of service then decreases over 5-year follow-up period (Den Dunnen, 1997; Walton & MacEntee, 1997; Davis & Packer, 2000; Karabuda et al., 2002).

A clear distinction between maintenance requirements of maxillary and mandibular overdentures has not been presented in the literature. This is relevant in view of the differences in the minimum number of implants required to support the prosthesis, degree of residual ridge resorption, residual ridge anatomy and the denture stress-bearing areas (Jacobson & Krol, 1983a; Jacobson & Krol, 1983b; Jacobson & Krol, 1983c; Çehreli et al., 2010). These aspects combined with the weighted advantage of mandibular overdentures in the literature may disguise the complexity of the prosthodontic maintenance requirements for maxillary implant overdentures.

Thus, in the next section of this part the prosthodontic maintenance requirements for maxillary implant overdentures using different prosthodontic designs was evaluated and systematically reviewed.

MATERIALS AND METHODS

Search Strategy

MEDLINE (1988 to April 2010), PubMed (using medical subject headings), and Google Scholar databases were searched using key words; “maxilla ± implant ± overdenture(s),” “oral ± dental ± implant(s),” “prosthodontic design(s),” and “prosthodontic ± maintenance ± complication” with the restriction of articles in English only. Other articles were identified
from the reference lists of the articles found using the aforementioned databases, supplemented by manual hand searching of the following dental journals: *British Dental Journal, Clinical Implant Dentistry and Related Research, Clinical Oral Implants Research, Implant Dentistry, International Journal of Oral and Maxillofacial Implants, International Journal of Oral and Maxillofacial Surgery, International Journal of Periodontics and Restorative Dentistry, International Journal of Prosthodontics, Journal of American Dental Association, Journal of Clinical Periodontology, Journal of Dental Research, Journal of Oral Implantology, Journal of Oral and Maxillofacial Surgery, Journal of Prosthodontics, Journal of Prosthetic Dentistry and Journal of Periodontology*. The titles and abstracts (when available) of all reports identified through the electronic search were scanned. For studies appearing to meet the inclusion criteria, or for which there were insufficient data in the title and abstract to make a clear decision, the full report was obtained. All the information was assessed to establish whether the studies met the inclusion criteria. Unanimous agreement between the reviewers regarding the included studies was achieved.

Specific inclusion and exclusion criteria used during the literature search were as follows:

**Inclusion**

1. Randomized controlled trials, prospective and retrospective studies on completely edentulous maxilla rehabilitated with an implant overdenture
2. Studies reporting prosthodontic maintenance only on maxillary implant overdentures and no combined data with fixed prostheses or mandibular overdentures
3. English language only
4. No restrictions on the status of the mandible in terms of opposing prostheses or status of natural dentition
5. No restriction on the minimum observation period

**Exclusion**

1. Any studies on maxillary implant overdentures used to rehabilitate maxillofacial defects
2. Studies reporting on maintenance requirements of maxillary and mandibular implant overdentures combined together.

**RESULTS**

A total of 58 relevant studies on maxillary implant overdentures were identified, out of which 28 reported on maintenance requirements (*Engquist et al.*, 1988; *Naert et al.*, 1991;
Jemt et al., 1992; Johns et al., 1992; Tolman & Laney, 1992; Jemt, 1993; Smedberg et al., 1993; Palmqvist et al., 1994; Jemt & Lekholm, 1995; Zarb & Schmitt, 1996; Eksfeldt et al., 1997; Toljanic et al., 1997; Watson et al., 1997; Bergendal & Engquist, 1998; Naert et al., 1998; Watson et al., 1998; Smedberg et al., 1999; Zitzmann & Marinello, 2000; Kiener et al., 2001; Narhi et al., 2001; Attard & Zarb, 2004; Widbom et al., 2005; Ahlgren et al., 2006; Aykent et al., 2007; Karabuda et al., 2008; Krennmair et al., 2008; Visser et al., 2009; Akça et al., 2010). On reviewing the abstracts of these articles, 18 studies fulfilled the inclusion criteria (Naert et al., 1991; Jemt et al., 1992; Johns et al., 1992; Jemt, 1993; Smedberg et al., 1993; Palmqvist et al., 1994; Toljanic et al., 1997; Watson et al., 1997; Naert et al., 1998; Smedberg et al., 1999; Zitzmann & Marinello, 2000; Kiener et al., 2001; Närhi et al., 2001; Widbom et al., 2005; Ahlgren et al., 2006; Krennmair et al., 2008; Visser et al., 2009; Akça et al., 2010) while 10 articles were excluded as the data reported were mixed with that of either fixed implant bridges (2) (Tolman & Laney, 1992; Jemt & Lekholm, 1995) or mandibular overdentures (8) (Engquist et al., 1988; Zarb & Schmitt, 1996; Eksfeldt et al., 1997; Bergendal & Engquist, 1998; Watson et al., 1998; Attard & Zarb, 2004; Aykent et al., 2007; Karabuda et al., 2008) which prevented analysis of data focused on maxillary overdentures maintenance requirements only (Table 1.4). The included articles were 8 prospective (Johns et al., 1992; Toljanic et al., 1997; Watson et al., 1997; Naert et al., 1998; Zitzmann & Marinello, 2000; Ahlgren et al., 2006; Visser et al., 2009; Akça et al., 2010) and 10 retrospective studies (Naert et al., 1991; Jemt et al., 1992; Jemt, 1993; Smedberg et al., 1993; Palmqvist et al., 1994; Smedberg et al., 1999; Kiener et al., 2001; Närhi et al., 2001; Widbom et al., 2005; Krennmair et al., 2008). The definition of prosthodontic maintenance of maxillary overdenture had been historically broadly classified into mechanical complications, prosthesis-related adjustments, and soft tissue problems (Watson et al., 1997; Smedberg et al., 1993) with subjective complaints such as phonetics, esthetics and aspects of the opposing prostheses maintenance (Smedberg et al., 1993; Eksfeldt et al., 1997). The patraxis designs, number and size of the matrices were often not specified. Prosthodontic maintenance of patrices and matrices represented the cardinal aspects of the studies reviewed. Adjustment and contouring of denture flanges, and relining were usually performed following wear and activation or replacement of matrices. The longest follow-up within the included studies was 10 years and the shortest was 3 months.

**Maintenance of matrices**

The adjustment or repair of loosened/fractured matrices of attachment systems dominated the identified studies (Naert et al., 1991; Jemt et al., 1992; Johns et al., 1992; Palmqvist et al., 1994; Jemt & Lekholm, 1995; Zarb & Schmitt, 1996; Eksfeldt et al., 1997; Toljanic et al., 1997; Watson et al., 1997; Bergendal & Engquist, 1998; Naert et al., 1998; Watson et al., 1998; Smedberg et al., 1999; Zitzmann & Marinello, 2000; Kiener et al., 2001; Narhi et al., 2001; Attard & Zarb, 2004; Widbom et al., 2005; Ahlgren et al., 2006; Aykent et al., 2007; Karabuda et al., 2008; Krennmair et al., 2008; Visser et al., 2009; Akça et al., 2010). On reviewing the abstracts of these articles, 18 studies fulfilled the inclusion criteria (Naert et al., 1991; Jemt et al., 1992; Johns et al., 1992; Jemt, 1993; Smedberg et al., 1993; Palmqvist et al., 1994; Toljanic et al., 1997; Watson et al., 1997; Naert et al., 1998; Smedberg et al., 1999; Zitzmann & Marinello, 2000; Kiener et al., 2001; Närhi et al., 2001; Widbom et al., 2005; Ahlgren et al., 2006; Krennmair et al., 2008; Visser et al., 2009; Akça et al., 2010) while 10 articles were excluded as the data reported were mixed with that of either fixed implant bridges (2) (Tolman & Laney, 1992; Jemt & Lekholm, 1995) or mandibular overdentures (8) (Engquist et al., 1988; Zarb & Schmitt, 1996; Eksfeldt et al., 1997; Bergendal & Engquist, 1998; Watson et al., 1998; Attard & Zarb, 2004; Aykent et al., 2007; Karabuda et al., 2008) which prevented analysis of data focused on maxillary overdentures maintenance requirements only (Table 1.4). The included articles were 8 prospective (Johns et al., 1992; Toljanic et al., 1997; Watson et al., 1997; Naert et al., 1998; Zitzmann & Marinello, 2000; Ahlgren et al., 2006; Visser et al., 2009; Akça et al., 2010) and 10 retrospective studies (Naert et al., 1991; Jemt et al., 1992; Jemt, 1993; Smedberg et al., 1993; Palmqvist et al., 1994; Smedberg et al., 1999; Kiener et al., 2001; Närhi et al., 2001; Widbom et al., 2005; Krennmair et al., 2008). The definition of prosthodontic maintenance of maxillary overdenture had been historically broadly classified into mechanical complications, prosthesis-related adjustments, and soft tissue problems (Watson et al., 1997; Smedberg et al., 1993) with subjective complaints such as phonetics, esthetics and aspects of the opposing prostheses maintenance (Smedberg et al., 1993; Eksfeldt et al., 1997). The patraxis designs, number and size of the matrices were often not specified. Prosthodontic maintenance of patrices and matrices represented the cardinal aspects of the studies reviewed. Adjustment and contouring of denture flanges, and relining were usually performed following wear and activation or replacement of matrices. The longest follow-up within the included studies was 10 years and the shortest was 3 months.

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A prospective multicenter overdenture study involving 133 participants using different number of implants noted clip fracture in 6 participants, while 8 maxillary implant overdentures required bar-clip activations on one or more occasions during the first year of function (Johns et al., 1992). Jemt et al. (1992) investigated 91 maxillary overdentures and reported bar-clip retention problems (17%) and bar-clip fracture (22%) during the first year of function. This resulted in recommendation of the inclusion of a spacer to allow vertical resiliency and to reduce the loading on the acrylic resin of the clip and its surroundings to reduce the fracture of the denture base. Keiner et al. (2001) reported an average of 2.1 adjustments/repairs of matrices per splinted/unsplinted designs for maxillary overdentures over a mean observation period of 3.2 years. They also noted that 50% of the maintenance requirements were recorded for 20% of the participants (Ekfeldt et al., 1997).

Studies using a specific planned approach of maxillary implant overdentures supported by milled bars and metal reinforcements showed a reduced incidence of prosthodontic maintenance requirements of bar-clip activation or renewal of the attachment system (Smedberg et al., 1999; Krennmair et al., 2008). One group also found increased maintenance required for overdentures with 6 to 8 implants placed in the grafted maxillary molar regions as compared to 4 implants placed in the anterior maxillary regions (Krennmair et al., 2008). Others reported minor adjustments of attachments (Ceka, Preat Corp, CA, USA) and oral hygiene measures to be the only aftercare needed for maxillary implant overdentures during the 10-year follow-up (Visser et al., 2009). Naert et al. (1998) reported that the most frequent prosthodontic complication with hinging overdenture designs was the wear of the attachments that necessitated activation or replacement of the attachment systems.

The frequency of matrix replacements varied and was unclear whether it was determined subjectively by the patient or objectively by the clinician. In a retrospective study, 50% of patients did not request any matrix replacement for more than 5 years, whereas the other half required replacement of the resilient matrices bimonthly owing to unsatisfactory retention (Widbom et al., 2005). The mean time in service reported before matrix replacements was 21.5 months (Widbom et al., 2005).

**Maintenance of patrices**

The wear and fracture or failure of patrices was notably less frequent than that of matrices in the selected studies. For the splinted implant overdenture designs, evidence of low failure
rates of inter-abutment connecting bars, but higher failure rates of distal cantilever extensions were clearly identified (Kiener et al., 2001). Kiener et al. (2001) reported the fracture of 2 inter-abutment U-shaped Dolder bars compared to 8 fractured distal bar extensions in 33 maxillary implant overdentures during the 2-year service. However, reasons for these fractures and the specific fracture sites were not reported. Low incidence of bar fractures at the bar-abutment junction was noted in several studies attributed to inadequate soldering or casting at the junction between the abutment cylinder and bars (Jemt et al., 1992; Watson et al., 1997; Akça et al., 2010).

Visser et al. (2009) modified their attachment design from a milled gold-alloy bar with Ceka attachments to a thick egg-shaped milled solid titanium bar to avoid complications and technical difficulties associated with the Ceka attachment and the bar superstructure. Only one study reported the wear of ball abutments on top of a bar superstructure in more than 33% of the participants despite using resilient matrices (Widbom et al., 2005). The authors attributed this wear to the overdenture design with partial palatal coverage and the material used for the fabrication of bar and ball attachments.

The studies reported abutment screw loosening with implant overdentures (Naert et al., 1991; Jemt et al., 1992; Palmqvist et al., 1994; Naert et al., 1998; Smedberg et al., 1999; Kiener et al., 2001; Krennmair et al., 2008). Smedberg et al. (1999) noted 5 out of 8 patients with maxillary overdentures needed tightening of implant abutment screws after 2 years of function. Others also reported retightening of abutment screws to be the most frequent mechanical complication encountered with maxillary implant overdentures supported by bars (Kiener et al., 2001). They detected 6 out of 41 overdentures and 5 out of 34 overdentures with screw loosening in the first and second year of service, respectively. Krennmair et al. (2008) reported an incidence of 5% abutment screw loosening after a mean observation period of 5 years.

**Inter-abutment distance**

The inter-abutment distance and its influence on maxillary overdenture patrix and matrix maintenance were not addressed in the majority of studies. Naert et al. (1991) used an inter-abutment distance of 24–39 mm along the ridge when using 2 or 3 unsplinted implants. Nā rhi et al. (2001) speculated that with splinted design an increased inter-abutment distance would cause loss of connecting bar rigidity, more complex stress distribution, and higher incidence
of abutment screw loosening. However, they still did not recommend an ideal inter-abutment distance.

Relines

Jemt et al. (1992) found relining to be needed for 24% of maxillary implant overdentures in the first year of function to compensate for the residual ridge resorption under the distal extension areas, as well as improving the adaptation of prostheses to underlying tissues. Other reports noted that 40% of maxillary implant overdentures required relining within 3 years (Smedberg et al., 1993).

Fracture of overdenture bases

Higher incidence of denture base fracture of maxillary prostheses relative to mandibular counterpart has been demonstrated especially in case of reduced palatal coverage and absence of metal reinforcement (Watson et al., 1997; Widbom et al., 2005). Jemt et al. (1992) reported 14% of participants with acrylic resin fracture around clips and another study showing resin base and resin tooth fracture to be the most frequently encountered complications with spark erosion maxillary overdentures over 5 years (Toljanic, 1997).

Mucosal complications

The most common mucosal complications reported with maxillary implant overdentures were hyperplasia, irritations, and denture stomatitis, independent of the type of attachment systems (Naert et al., 1991; Jemt et al., 1992; Johns et al., 1992; Smedberg et al., 1993; Watson et al., 1997; Naert et al., 1998; Zitzmann & Marinello, 2000; Kiener et al., 2001; Närhi et al., 2001; Widbom et al., 2005, Visser et al., 2009). Denture stomatitis was reported at 31% (Watson et al., 1997). A retrospective study involving bars revealed a high incidence of hyperplasia in 64–67% of participants over a 5-year observation period (Widbom et al., 2005). Zitzmann and Marinello (2000) noted hyperplasia in 2 out of 10 participants with a splinted design at 6-month interval and stressed the importance of longer observation period to minimize further complications related to mucosal hyperplasia.

Planned versus emergency maxillary overdentures

Two studies reported on the maintenance requirements of maxillary overdentures in 2 different situations; when planned as a first line of treatment and when indicated as a rescue
replacement for fixed prostheses. No difference was found in mechanical complications between the 2 groups. The reported mean time in service of nylon attachments was 21.5 months and 18 months for the two groups respectively. However, regarding soft tissue complications, Widbom et al. (2005) found that hyperplasia was more common among subjects originally planned for overdentures (67%) opposed to those receiving emergency overdentures treatment (40%). On the other hand, Palmqvist et al. (1994) reported no difference in soft tissue complications between both groups.

Time and cost

With exception to 2 studies discussing the time involved in prosthodontic aftercare of maxillary implant overdentures, time and cost implications were scarce in the literature. No studies could be identified describing the cost involved with long-term maintenance of maxillary overdentures (Jemt, 1993). Visser et al. (2009) reported an average aftercare time per patient of 443 minutes starting at 2-month period after overdenture insertion until the end of 10-year follow-up. This included only the dental chair time. Another study compared the number of clinical appointments between patients receiving maxillary overdentures as a final treatment, as opposed to an intermediate overdenture group where it was later replaced with fixed implant prostheses. The authors identified that fewer appointments were needed for the intermediate group during the first year of function while the situation was reversed for the second and third year of follow-up.
<table>
<thead>
<tr>
<th>Study</th>
<th>Type of Study</th>
<th>Maximum Observation Period (Months)</th>
<th>Number of Participants</th>
<th>Total Number of Implants</th>
<th>Number of Implants in Maxilla</th>
<th>Attachment System</th>
<th>Palatal Coverage</th>
<th>Status of Opposing Jaw</th>
<th>Prosthodontic Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jemt et al 1992</td>
<td>Retro</td>
<td>12</td>
<td>92</td>
<td>430</td>
<td>Unplanned</td>
<td>Splinted: Bar (90) Unsplinted: Ball (1) Magnet (1)</td>
<td>Not mentioned</td>
<td>Not mentioned</td>
<td>Soft tissue: Ulceration (33%) Hyperplasia (7%) Mechanical: Clip fracture (22%) Clip activation (10%; 1x; 4%, 2x; 3%, 3x) Overdenture fracture (3%) Denture tooth fracture (2%) Bar fracture (1%) Acrylic resin fracture around clips (11%) Loose abutment screws (3%)</td>
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<tr>
<td>Study</td>
<td>Year</td>
<td>Type</td>
<td>Number</td>
<td>Period</td>
<td>Splinted Details</td>
<td>Occlusal Adjustment</td>
<td>Relining</td>
<td>Soft Tissue Problems</td>
<td>Mechanical Problems</td>
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<tr>
<td>Smedberg et al 1993</td>
<td>32</td>
<td>18</td>
<td>86</td>
<td>4 – 6</td>
<td>Splinted: Tapered milled bar</td>
<td>Not mentioned</td>
<td></td>
<td>Soft tissue: Denture stomatitis (1)</td>
<td>Mechanical: Attachment activation (10) Attachment replacement (6)</td>
</tr>
<tr>
<td>Study</td>
<td>Pro</td>
<td>29</td>
<td>117</td>
<td>Not mentioned</td>
<td>Splinted: Cast/wrought bars (round/oval/U-shaped) Straight/curved/angular bars</td>
<td>Complete acrylic resin</td>
<td>Natural dentition Overdenture</td>
<td>Soft tissue: Hyperplasia, denture stomatitis, soreness, ulceration</td>
<td>Mechanical: Overdenture fracture (8; 17x) Clip fracture (10; 17x) Bar fracture (1) Dislodged clip (8; 17x) Clip activation (11; 33x)</td>
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<tr>
<td>Naert et al 1998</td>
<td>Pro</td>
<td>48</td>
<td>13</td>
<td>53 Minimal 4</td>
<td>Rigid cast bar &amp; 2 attachments placed distally to abutment</td>
<td>Various</td>
<td>Soft tissue: Hyperplasia, denture stomatitis, soreness, ulceration</td>
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<td>Full or partial dentition (8) Implant overdenture on two implants (1) Fixed implant prosthesis (2) Complete denture (2)</td>
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<td>Mechanical: Attachment wear &amp; replacement (17) Attachment activation (10) Loose abutment screws (1)</td>
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<td>Denture adjustment: Relining &amp; rebasing (8; 16x)</td>
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<tr>
<td>Study</td>
<td>Type</td>
<td>Year</td>
<td>Patients</td>
<td>Mean Age</td>
<td>Splinted:</td>
<td>Double Denture Framework</td>
<td>Soft Tissue</td>
<td>Mechanical</td>
<td>Denture Adjustment</td>
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<tr>
<td>Smedberg et al 1999</td>
<td>Retro</td>
<td>1999</td>
<td>72</td>
<td>28</td>
<td>Splinted: Tapered cast &amp; milled gold alloy bar</td>
<td>Horseshoe (Co-Cr framework)</td>
<td>Not mentioned</td>
<td></td>
<td></td>
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<tr>
<td>Zitzmann &amp; Marinello 2000</td>
<td>Pro</td>
<td>2000</td>
<td>27</td>
<td>10</td>
<td>Splinted:</td>
<td>Various (depending on speech)</td>
<td>Not mentioned</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Study</td>
<td>Type</td>
<td>N</td>
<td>M</td>
<td>F</td>
<td>Splinted/Unsplinted</td>
<td>Complete coverage</td>
<td>Natural dentition with/without removable partial denture</td>
<td>Tooth supported overdenture</td>
<td>Implant supported/retained overdenture</td>
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<tr>
<td>Närhi et al 2001</td>
<td>Retro</td>
<td>54</td>
<td>16</td>
<td>88</td>
<td>Not mentioned</td>
<td>Bar (11)</td>
<td>Complete coverage (9)</td>
<td>Natural dentition with/without removable partial denture</td>
<td>Tooth supported overdenture</td>
</tr>
<tr>
<td>Krennmar et al 2008</td>
<td>Retro</td>
<td>42.1 ± 20.1</td>
<td>34</td>
<td>179</td>
<td>4 – 8</td>
<td>Splinted: Anterior milled bars with cantilevers or Two bilateral posterior milled bars</td>
<td>Horseshoe (reinforced with cast framework)</td>
<td>Not mentioned</td>
<td>Mechanical:</td>
</tr>
<tr>
<td>Study</td>
<td>Prospective/Retrospектив</td>
<td>Pro</td>
<td>120</td>
<td>39</td>
<td>234</td>
<td>6</td>
<td>Splinted:</td>
<td>Partial:</td>
<td>Implant overdenture on 4 implants (17)</td>
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<tr>
<td>Visser et al 2009</td>
<td>Pro</td>
<td>48.5</td>
<td>11</td>
<td>44</td>
<td>4</td>
<td></td>
<td>Splinted: Egg-shaped prefabricated gold Dolder bar with cantilever (1)</td>
<td>Partial:</td>
<td>Implant overdenture on 4 implants (17)</td>
</tr>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Egg-shaped cast gold Dolder bar with cantilever (10)</td>
<td>Not mentioned</td>
<td>Implant overdentures (4)</td>
</tr>
</tbody>
</table>

Pro: prospective
Retro: retrospective
Co-Cr: cobalt-chromium
x: Occasions

Occlusal adjustment (3)
Rebasing (2)

Soft tissue: Sore spots

Mechanical: Attachment activation (50%) Attachment repair (25%)

Denture adjustment: Replacement overdenture (23%)
This literature review was conducted to examine studies specifically related to prosthodontic maintenance requirements of maxillary implant overdentures with different designs. This review is the first to evaluate maxillary overdenture maintenance requirements as a separate entity, not mixed with those of mandibular counterparts or fixed full arch implant bridges. This identifies a cornerstone of a topic that is relatively deficient in the literature. On the other hand, limitations with this review also need to be addressed. The bias towards English language literature is acknowledged. This could result in omission of some relevant data relevant to the topic in hand. Another limitation addressed is the insufficient data available for comparative analysis due to limited number of studies included with their small sample size. Furthermore, the lack of standardization in the assessment of prosthodontic outcomes among studies resulted in drawing general recommendations rather than coming up with definite conclusions.

This review finds that prosthodontic maintenance requirements of maxillary implant overdentures are a direct consequence of attachment systems, different number and distribution of implants. Uncertainty exists as what constitutes acceptable maintenance or repair, and whether either of these categories should be considered as retreatment (Attard & Zarb, 2004). Various definitions of adjustment have been proposed ranging from any treatment to the denture that did not involve the addition of new material or the replacement of broken or missing components (Walton & MacEntee, 1997; Walton et al., 2002). Walton & MacEntee (1997) although principally addressing mandibular implant overdentures, categorized adjustments as those events needed to adjust the denture contour, correct the occlusion or tighten the components, whereas repair events were related to lost, loose or fractured retentive clips and relines. Others, on the other hand, quantitatively differentiated between maintenance and complications depending on the number of the appointments needed; in such a way that if excessive amount of maintenance is needed it would be categorized as complications and failure of prostheses (Kiener et al., 2001). Another classification based its prosthodontic complications on the severity: major non-retrievable, major retrievable and minor retrievable (Tolman & Laney, 1992). Major non-retrievable complications included implant fracture and failure of osseointegration. Major retrievable complications involved acrylic resin and tooth wear, retentive matrix fracture, overdenture fracture or detachment while minor retrievable complications comprised of retentive bar-clip loosening and acrylic resin tooth fracture. This range of categorization makes comparison between different studies difficult and attests the need for more universally accepted
evaluation criteria for data reporting. The wide range of terminology used to describe the post-insertion maintenance events and lack of strict categorization made it difficult to establish success of maxillary implant overdentures in terms of maintenance requirements and complications (Mericske-Stern, 1998; Bryant et al., 2007; Akça et al., 2010; Çehreli et al., 2010). Furthermore, we recommend that prosthodontic complications of maxillary implant overdentures should be reported separately from the mandibular implant overdentures and distinguish its unique maintenance issues from the fixed counterparts (Ekfeldt et al., 1997; Goodacre et al., 2003; Karabuda et al., 2008). A detailed categorization for prosthodontic maintenance for implant overdentures was proposed by Payne et al. (2001a) in which an existing classification for fixed full-arch implant prostheses using the 6 objectively defined fields of success, survival, unknown, dead, and retreatment was adapted. This protocol would allow a detailed description of prosthodontic maintenance requirements and time to retreatment regardless of design, type of attachment, or implant system used.

Maintenance of attachment systems and denture adjustments were the most frequently encountered post-operative maintenance requirements (Tolman & Laney, 1992; Toljanic et al., 1997; Walton & MacEntee, 1997; Watson et al., 1997; Bergendal & Engquist, 1998). The ability to differentiate between the extent of maintenance required among different unsplinted attachment systems have been limited by the lack of standardization in recording criterion, length of observation period, and small number of participants in most of the studies (Palmqvist et al., 1994; Ekfeldt et al., 1997; Bergendal & Engquist, 1998; Naert et al., 1998; Attard & Zarb, 2004). Moreover, a repeated frequency of maintenance events reported for a particular group of participants have indicated the subjective nature of these prosthodontic complications (Johns et al., 1992; Kiener et al., 2001). Nonetheless, the findings reported in some of the early studies should be cautiously viewed due to the rapid ongoing developments of the attachment systems, which had a bearing on the number of maintenance events encountered.

Mechanical complications though may be minor or reversible, can be time consuming and financially burdening for patients. These complications may indicate that the design concept is inappropriate, the mechanical or material components are incompatible, or the occlusal scheme and masticatory function are not in harmony (Walton & MacEntee, 1997).

When comparing rigid and resilient overdenture designs, the reduced amount of maintenance requirements for the rigid design may be attributed to the prosthesis design
which had a frictional over-casting that did not allow prosthesis rotation, thus reducing the wear on the clips (Krennmair et al., 2008). This was corroborated by another study that reported increased incidence of wear of the attachments with a hinging overdenture design (Naert et al., 1998). Moreover, rigid overdenture designs tend to be implant-supported with increased implant number rather than solely mucosa-supported, which reduces the need for the relief of sore spots and denture relines (Visser et al., 2009). Differences in maintenance reported between milled gold-alloy bars with Ceka attachments to solid titanium bars could be attributed to the physical properties of materials used (Visser et al., 2009). This is supported by findings of Widbom et al. (2005) who recommended a harder and more resistant metal alloy for superstructure construction than hard gold alloy used in their study to reduce the need for maintenance.

Controversy still exists in terms of prosthodontic maintenance requirements when comparing splinted and unsplinted designs. A lack of standardized superstructure design within a study and between different studies, combined with small number of participants did not allow any definite conclusion regarding the most effective mode of attachment systems (Henry, 1998; Närgi et al., 2001). However, studies reporting on maintenance requirements for maxillary and mandibular overdentures combined, described a higher incidence of prosthodontic complications for ball attachments compared to bars (77.5% versus 42.9%) (Nedir et al., 2006). The number of maintenance events per prosthesis was 1.5 for ball attachments opposed to 0.9 for bar-retained overdentures (Nedir et al., 2006). Corrosion, wear and rapid loss of retention have frequently been reported with magnet attachment systems (Naert et al., 1991).

Comparative controlled trials comparing plastic and metal clips in terms of prosthodontic maintenance requirements are lacking and encouraged. An in-vitro study comparing metal and plastic clips revealed no complications after three years of simulated function (Walton & Ruse, 1995). The authors suggested that in clinical situations the malfunction of clips may be due to heavy functional and parafunctional loading, improper fit of denture bases, non-parallel/misaligned implants, and changes in the supporting tissues (Walton & Ruse, 1995). On the other hand, some clinical reports found a lower frequency of technical complications with metal clips compared to other types of resilient retention systems (Jemt et al., 1992; Ekfeldt et al., 1997; Watson et al., 1997). This could be explained by the fact that metal clips can be easily adjusted to improve the retention. Nonetheless, resilient attachment systems are
more economical, easily replaced, and may produce less wear of their respective patrices than metal clips (Block et al., 1990; Walton & Ruse, 1995; Widbom et al., 2005).

Relines and remakes, although subjective in clinical assessment, are long-term clinical maintenance of maxillary implant overdentures. In an attempt to facilitate the objective assessment that indicates the need of relines, Payne et al. (2001a) proposed some criteria that aids in decision making rather than relying solely on patients’ subjective evaluation (Attard & Zarb, 2004) thus allowing more valid comparison between studies. Remake of overdentures will also be largely dependent on professional judgment and experience, corresponding to similar objective measures developed for assessing conventional complete denture treatment (de Baat et al., 1997).

Maxillary implant overdenture base fracture has been reported frequently due to the reduced bulk of acrylic resin to accommodate attachment systems that impart greater load on the prosthesis base (Jemt, 1993; Watson et al., 1997). Several techniques and materials such as cast metal reinforcement of denture base have been adopted (Krämer et al., 1992; Mericske-Stern, 1998; Naert et al., 1998; Smedberg et al., 1999; Mericske-Stern et al., 2002; Krennmair et al., 2008) albeit contradicting reports on its efficacy and possibility of implant overloading (Naert et al., 1991; Davis & Packer, 1999; Kiener et al., 2001; Walton et al., 2002). Fiber-reinforced denture bases have also been recommended to improve the mechanical strength of the prosthesis (Vallittu, 1996, 1999; Stipho, 1998). However, further research is still required to show the clinical effectiveness of this technique.

The higher incidence of mucosal hyperplasia associated with maxillary splinted implant overdenture design can be attributed to design consideration (Jemt et al., 1992; Johns et al., 1992; Naert et al., 1998; Mericske-Stern et al., 2002). Bar placement close to mucosa and a negative pressure gradient in the dead space underneath the bar has been hypothesized to be the main reasons for the poor mucosal response (Engquist et al., 1988; Jemt et al., 1992; Johns et al., 1992). Patient reluctance to remove their prostheses has also been claimed to be a contributing factor for the increased hyperplasia (Naert et al., 1991). Likewise the higher percentage of hyperplasia reported for planned maxillary overdentures compared to the emergency treatments could be explained by the fact that the overdenture treatments are usually related to severe alveolar atrophy (Widbom et al., 2005). Such atrophy is frequently associated with more loosely attached mucosal tissues resulting in higher incidence of
hyperplastic tissue. However, owing to small sample size and lack of a statistical significance, this finding should be cautiously viewed.

A critical appraisal of the literature reveals a variety of terms used to describe changes in peri-implant mucosa such as gingival hyperplasia (Naert et al., 1998) mucosal proliferation (Smedberg et al., 1993) or mucosal hyperplasia (Jemt & Lekholm, 1995). Although these terms have become a part of the evidence-based literature, there is no histological evidence to support the descriptive terminology. The alternative term mucosal enlargement proposed by Payne et al. (2001b) is appropriate and more descriptive. Differences in methods used to record soft tissue parameters have tended to prevent correct interpretation of the outcomes. However, peri-implant soft tissue health was found to be independent of the type of the attachment system (Närhi et al., 2001; Çehreli et al., 2010). Nonetheless, published evidence shows a higher plaque index associated with magnet attachments (Trakas et al., 2006). More favourable soft tissue outcome shown with zirconia abutments in the partially edentulous cases may be extrapolated for implant overdentures. This may be advantageous for the maintenance of the peri-implant soft tissue health, and an area for future research with application of standardized recording criterion and controlled prospective studies (Rimondini et al., 2002; Scarano et al., 2004).

The impact of palatal coverage on the prosthodontic maintenance events was not evaluated using comparative controlled trials and merits further investigation. Controversial reports on the extent of palatal coverage exist in the literature. Several authors advocated a superstructure design with reduced palatal coverage to avoid mucosal problems commonly found underneath maxillary overdentures and allow the preservation of oral sensations and improved patients’ satisfaction (Smedberg et al., 1999; Zitzmann & Marinello, 2000; Kiener et al., 2001; Mericske-Stern et al., 2002; Payne et al., 2004; Krennmair et al., 2008). Contradicting opinions contended that complete palatal coverage is more advantageous as it reduces the wear of attachments and minimizes the risk of base fracture which is frequently encountered with reduced palatal coverage (Watson et al., 1997; Widbom et al., 2005; Sadowsky, 2007).

Similarly, the status of the opposing dentition and its potential influence on the maintenance requirements has been overlooked in most of the studies. Nevertheless, when described no attempts were made to correlate it with the prosthodontic events encountered. This leaves a void in the literature that merits further investigation.
Abutment screw loosening remains as a significant maintenance issue (Jemt et al., 1992; Palmqvist et al., 1994; Naert et al., 1998; Smedberg et al., 1999; Goodacre et al., 2003). Promising and encouraging results achieved with single piece ceramic implants in the rehabilitation of partially dentate arches could represent an answer to this problem if the ceramic implants prove to be a feasible option for implant overdentures (Oliva et al., 2007; Oliva et al., 2008a; Pirker & Kocher, 2008).

Consensus is needed among prosthodontists to define what constitutes repairs and maintenance for implant overdentures. There is a need to limit and redefine the wide range of terminology used so that outcomes of different studies can be more reliably compared. Future clinical trials designed to evaluate prosthodontic maintenance requirements should be more standardized with regards to the superstructure design, palatal contour, attachment systems used and status of opposing jaw to enable more definite conclusions to be drawn. Cost and time factors involved with prosthodontic aftercare of maxillary overdentures should be evaluated to allow a predictable comparison with full-arch fixed prostheses over a long-term period. The influence of opposing jaw on maintenance requirements of maxillary implant overdentures should also be evaluated within randomized control trials.

**CONCLUSIONS**

Prosthodontic maintenance requirements of maxillary overdentures are a direct consequence of the attachment systems, together with differing numbers and distribution of implants. The reviewed literature does not provide a clear controlled indication of prosthodontic maintenance requirements of maxillary overdentures for different prosthodontic designs and attachment systems. Future standardization of maxillary implant overdenture design is recommended together with universally accepted criteria for reporting maxillary implant overdenture maintenance should be implemented to establish accurate comparative data analysis.
PART IV: Research Rationale & Objectives

RESEARCH RATIONALE

There is to date a lack of literature on randomized clinical trials with single-piece zirconia implants supporting maxillary and mandibular overdentures. An investigation of the outcomes of zirconia implants supporting overdentures is required, for edentulous individuals with proven allergy to titanium or those requesting a metal-free restoration.

A novel distribution of implants used for overdenture support in the maxilla and mandible is introduced. The rationale behind the proposed novel design is to optimize the load distribution regarding the brittle nature of zirconia implants and to minimize the potential prosthodontic maintenance events. However, an evaluation of the outcome of this novel approach can only be based on sound scientific findings from randomized clinical trials. Understanding the biomechanical behavior as well as the failure pattern of zirconia implants and participants’ perception of the different aspects of this treatment modality would provide evidence-based recommendations for the international application of this novel protocol (Fig 1.1).

RESEARCH OBJECTIVES

Objectives related to the randomized clinical trial

- To compare and contrast statistically significant difference between the one-year success rates for titanium and zirconia implants when used to support maxillary and mandibular overdentures.
- To evaluate radiographically the marginal bone level changes around titanium and zirconia implants when used to support maxillary and mandibular overdentures.
- To compare and contrast statistically significant difference between the one-year prosthodontic outcomes for titanium and zirconia implant overdentures.
- To evaluate the success rate of short dental implants (8 mm or less in length) in the posterior mandibular and mid-palatal regions.
Objectives related to the in-vitro study

- To compare and contrast biomechanical behavior between zirconia and titanium implants used for support of maxillary overdentures using a three dimensional finite element analysis (3D-FEA).
- To compare and contrast biomechanical behavior between suggested novel and conventional implant distributions in the maxilla when implants were used for overdenture support using 3D-FEA.
- To analyze, if it occurs, the fracture pattern of zirconia implants used for overdentures support, and to identify possible reasons and suggest recommendations to avoid such incidences in the future.

Objectives of qualitative study

- To qualitatively assess the participants perception of the different aspects of the proposed novel treatment modality.

Overall objectives of the research

- Formulate recommendations regarding the use of one-piece zirconia implants for the support of implant overdentures.
- Evaluate proposed prosthodontic designs involving novel implant distributions when implants are used for the support of maxillary and mandibular implant overdentures.
- Correlate the maintenance requirements of attachment systems with different implant materials and proposed novel prosthodontic designs.
Figure 1.1 Sequence & Interrelation of the proposed *In-Vitro & In-Vivo* Studies
CHAPTER II

In-vitro finite element analysis studies to validate research question

PART 1: Titanium versus Zirconia Implants Supporting Maxillary Overdentures: Three-Dimensional Finite Element Analysis

Publication status: *In press*

*Osman*, R.B., Elkhadem, A.H., Ma, S., Swain, M.V. Titanium versus zirconia implants supporting maxillary overdentures. Three-dimensional finite element analysis study. *Int J oral Maxillofac Implants; [In Press]*.
ABSTRACT

The purpose of this study was to evaluate the stress and strain distribution occurring in the peri-implant bone and implants used to support maxillary overdentures. Three-dimensional finite element analysis (3D-FEA) was used to compare one-piece zirconia and titanium implants. Two types of implants were simulated using 3D-FEA models: one-piece zirconia and titanium implants (Ø3.8 x 11.5mm) with 2.25 mm diameter ball abutments. In each simulation, four implants were placed bilaterally in the canine/premolar region of an edentulous maxillary model. Static loads were applied axially and 20° buccolingually on the buccal slope of the lingual cusps of posterior teeth in the first quadrant. Von Mises stresses and equivalent strains generated in peri-implant bone as well as first principal stresses in the implants were calculated. Comparable stress and strain values were shown in the peri-implant bone for both types of implants. The maximum equivalent strain produced in the peri-implant region was mostly within the range for bone augmentation according to Frost’s Mechanostat theory. Under oblique loading, maximum von Mises stress and equivalent strain were most evident at the neck of the most distal implant on the loaded side. Under axial load, the stress and strain were transferred to the peri-implant bone around the apex of the implant. Maximum tensile stresses occurring with either material were well below their fracture strength. The highest stress was mainly at the disto-buccal region of the implant neck under both oblique and axial loading conditions. From a biomechanical point of view, ceramic implants made from yttrium-stabilized tetragonal polycrystalline (Y-TZP) zirconia may be a potential alternative to conventional titanium implants to support maxillary overdentures. This is particularly relevant for a selected group of patients with allergy to titanium or for those cases requesting metal-free restorations. Prospective clinical studies are still required to confirm these in-vitro results. Different simulations presenting various cortical bone thickness and implant designs are required to provide a better understanding of the biomechanics of zirconia implants.
Commercially pure titanium (Cp-Ti) and its alloys as biomaterials of choice are the most commonly used materials for oral implants due to their suitable mechanical properties and biocompatibility (Steinemann, 1998; Özkurt & Kazazoğlu, 2011). Nevertheless, controversial reports of allergic reactions to titanium in addition to the rise in the concept of metal-free dentistry have propelled the search for an alternative implant material (Sicilia et al., 2008; Vagkopoulou et al., 2009; Siddiqi et al., 2011; Javed et al., 2013). Recently, a possible association between surface corrosion of titanium implants and subsequent ionic and/or particulate release with implant failures and hypersensitivity reactions has been reported. Titanium hypersensitivity has been described in the form of facial eczema, dermatitis, rashes, non-keratinized edematous hyperplastic gingiva and rapid implant exfoliation, which could not be attributed to infection, impaired healing or overload (Flatebø et al., 2006; du Preez et al., 2007; Egusa et al., 2008; Chaturvedi, 2009). It has been suggested that the incidence of allergic reaction to titanium dental implants (0.6%) may be under-reported as a possible aetiological factor in implant failure due to lack of recognition, infrequent and ambiguous clinical presentation (Sicilia et al., 2008; Vagkopoulou et al., 2009; Javed et al., 2011; Siddiqi et al., 2011). Thus, it would be prudent, till research proves otherwise, to use implants of alternative materials in patients with proven allergy to titanium.

Earlier, development of ceramic-based implants using aluminum oxide (Al₂O₃) was attempted (Kawahara & Hirabayashi, 1980; Koth et al., 1988; Sclaroff et al., 1990; Fratash et al., 1995, 1996; Steflik et al., 1995). Although these implants met the biological and physical requirements, their inferior mechanical properties and reduced survival rates compared to titanium implants led to their withdrawal from the market (Koth et al., 1988; Sclaroff et al., 1990; Fratash et al., 1996; Ichikawa et al., 1992; Berge & Grønningsæter, 2000; Koutayas et al., 2009). With the introduction of zirconia particularly the yttrium-stabilized tetragonal polycrystalline zirconia (Y-TZP), interest in ceramics as a material of choice has been renewed (Denry & Kelly, 2008; Hisbergues et al., 2009). Zirconia exhibits good physical and mechanical properties such as a high flexural strength (900–1200 MPa), hardness (1200 Vickers) and Weibull modulus (10–12) (Hisbergues et al., 2009). Stress induced transformation toughening is a unique characteristic of Y-TZP as it undergoes a phase transformation process resulting in local volume expansion and therefore counteracting crack propagation (Garvie et al., 1975; Piconi & Maccauro, 1999; Denry & Kelly, 2008).
Osseointegration of zirconia has been extensively evaluated in different animal models, under different loading conditions and various loading periods (Akagwa et al., 1993; Akagwa et al., 1998). These studies revealed that zirconia is osseoconductive presenting an appropriate substrate for the proliferation and the spreading of osteoblasts (Josset et al., 1999; Scarano et al., 2003; Kohal et al., 2004; Sennerby et al., 2005; Hoffmann et al., 2008). Zirconia facilitates bone formation that provides a bone-implant interface similar to that seen around commercially pure titanium (Bächle et al., 2007; Depprich et al., 2008; Gahlert et al., 2009). Various investigations of soft tissue response around zirconia have also revealed better healing response, less inflammatory infiltrate and reduced plaque adhesion on zirconium oxide discs compared to conventionally pure titanium (Rimondini et al., 2002; Scarano et al., 2004; Degidi et al., 2006, Größner-Schreiber et al., 2006).

Results of human clinical trials and case reports revealed favourable peri-implant marginal bone levels and soft tissue parameters of zirconia implants when used for rehabilitation of partially dentate patients, albeit in the short-term (Kohal & Klaus, 2004; Oliva et al., 2007, 2008a; Payer et al., 2012). Similar reports on the use of zirconia implants for support of overdentures are lacking and encouraged. However, before such a recommendation can be made it should be well supported with sufficient evidence. This can be partly achieved through well-designed in-vitro studies that evaluate the biomechanical behavior of zirconia implants when used for overdentures support.

A limited number of studies evaluated the loading response of zirconia implants and compared it to that of titanium implants (Kohal et al., 2002; Çağlar et al., 2011; Choi et al., 2012). Most of these studies focused on mechanical behavior of implants supporting single crowns either in the anterior maxillary or posterior mandibular region. To the authors’ knowledge, no studies are available in the literature investigating the difference in the biomechanical behavior between the two implant materials supporting overdentures.

Therefore, the purpose of this study was to analyze and compare the von Mises and equivalent strain occurring in peri-implant bone and first principal stress in implants using three-dimensional finite element analysis in two simulations: titanium and zirconia implants supporting maxillary overdentures.
MATERIALS AND METHODS

Model Design

A three-dimensional finite element analysis (3-D FEA) model of an edentulous maxilla restored with an implant overdenture was simulated using Cosmosworks 2007 (Solid Works Corporation UK). The maxillary model was constructed in two versions, the first version had four titanium (Ti) implants (3.8 mm x 11.5 mm) placed bilaterally in the area of former lateral and first premolar regions whereas in the second version zirconia (ZrO₂) implants of the same dimension and distribution was simulated. The maxillary models used in the FEA were derived from a series of axial sections of computerized tomography scan images (CBCT) of a completely edentulous maxilla. Eight modeling planes were selected perpendicular to the axial cross section. All the sections met at the posterior nasal spine posteriorly. The sections passed through the midline, lateral incisor, canine, premolar, molar and tuberosity regions. The last section ended at the pterygomaxillary notch. The location of the cut sections was identified with the aid of a radio-opaque setup of a scanned denture. The modeled geometry of the maxillary half was then mirrored about the midline to produce the full edentulous maxilla.

Initially, each component was modeled separately and ultimately all the components were assembled together. For this analysis, a dense fine trabecular bone with no cortical layer was assumed as maxillary models that have a cancellous core with mechanical properties of magnitude less than that of the overlying cortical layer may behave as if the implants are supported only by the cortical bone and the reaction force within the cancellous bone would be underestimated (Clelland et al., 1993; Meyer et al., 2001; Saab et al., 2007). The mucosal layer was designed with varying thickness to simulate a more realistic clinical situation (Cheng et al., 2010).

Bone cylinders that are 1 mm wider than the corresponding implant diameter and 2 mm longer than the intra-bony portion of the implant were created. The geometry of the intra-bony portion of the implant was engraved and centralized inside these cylinders (Fig 2.1a). This component served two purposes. First it facilitated the placement of the implant into its exact target position inside the maxillary bone. Second, it can be recognized as a separate entity so that the stresses in the peri-implant bone can be easily determined. Four cuts were then made into each maxillary model at the proposed implant sites and corresponding to the size of bone cylinders (Fig 2.1b).
The implants and attachments were modeled according to the specifications provided by the manufacturer (Southern Implants, Irene, South Africa) for actual one-piece zirconia and titanium implants specifically manufactured for the use in an *in-vivo* study to be conducted by our research group (Fig 2.2). The original design data was then used to CAD the implants with no need for sophisticated scanning procedures. Due to manufacturing limitations zirconia can only be provided as one-piece implant opposed to its titanium counterpart (Kohal *et al.*, 2018).
Thus, to avoid the influence of different implant designs on the results, titanium one-piece implants were also used and simulated.

The denture was designed to provide full palatal coverage. The average prosthesis height was 15 mm. The positions of the nylon caps were engraved inside the fitting surface of the denture while ensuring at least 2mm of acrylic above the caps.

All of the modeled components were then assembled together. The implants with their corresponding bone cylinders and nylon caps were first mated into one assembly (Fig 2.3a). The former assembly was then located inside the corresponding cuts made inside the maxillary bone (Fig 2.3b). The mucosa was then mated over the maxilla (Fig 2.3c). Finally the overdenture was seated over the whole assembly (Fig 2.3d).
Elements and Nodes

The models were meshed with 3-D parabolic tetrahedral solid elements with surface-to-surface contact to produce a high quality solid mesh. The total number of elements and nodes were 688993 and 950303 respectively. The average element size used was 0.9 mm with 0.045 mm tolerance. The border between the implant and the maxillary bone was fine meshed at the edges to ensure accuracy of the analysis.
Material Properties

In the absence of information concerning the precise properties of maxillary bone, it was assumed to be isotropic, homogenous and linearly elastic, as were the other materials used in this analysis. Table 2.1 shows the Young’s modulus and Poisson’s ratio values identified for each material simulated in this study, as obtained from previously published data (Geng et al., 2001). The material properties of zirconia implants and attachment systems were provided by the manufacturer (Southern Implants, Irene, South Africa).

Boundary Conditions

All the components were assumed to exhibit a fixed bond at the interface with the contacting structures except for the attachment system (plastic cap)/implant and overdenture/mucosal interfaces where a no penetration sliding (friction coefficient of 0.3) contact was defined (Chun et al., 2005). The implants were assumed to be completely osseointegrated with 100% contact to the bone at the interface while the overdenture and attachment systems were allowed to move freely on top of mucosa and implants respectively (Fig 2.4) (Saab et al., 2007).

![Figure 2.4 Cross-section view showing relationship between ball abutment and plastic cap](image)

(a) An arrow pointing to the space between the flat head of the ball abutment and the plastic cap permitting vertical compression of cap under vertical occlusal load.

(b) An arrow pointing to the lack of contact between the implant neck and the side walls of the plastic cap which allows limited lateral movement.
Constraints and Loads

The entire assembly was restrained at the superior aspect of the maxilla to avoid total body displacement under load. This site was chosen as it represents the contact of the maxilla with the base of the skull, which limits the movement of the maxilla. Moreover, the restraint being located sufficiently away from the loading area allows strain transmission and minimizes influence on the generated stresses (Saab et al., 2007).

Loads of 300 N (75 N per premolar and 150 N for the first molar) were applied axially on the fossa of acrylic denture teeth (Fig 2.5a) and 20° buccolingually on the buccal slope of the lingual cusps of posterior teeth (Fig 2.5b) of the first quadrant.

Finite element iterative solver software (FFE plus solver) was used to compute von Mises stress and equivalent strain occurring in the peri-implant bone as well as the first principal stresses in the implants of each model. The data was then collected and color-coded for comparative evaluation.

Table 2.1 Assumption for the FEA model

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Modulus of elasticity (MPa)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maxillary bone</td>
<td>Cancellous bone</td>
<td>1,370</td>
<td>0.3</td>
</tr>
<tr>
<td>Mucosal layer</td>
<td>Oral mucosa</td>
<td>10</td>
<td>0.4</td>
</tr>
<tr>
<td>Zirconia implants*</td>
<td>Zirconia</td>
<td>220,000</td>
<td>0.31</td>
</tr>
<tr>
<td>Titanium implants*</td>
<td>Grade IV Cp-Ti</td>
<td>104,000</td>
<td>0.3</td>
</tr>
<tr>
<td>Plastic cap*</td>
<td>Nylon</td>
<td>70</td>
<td>0.4</td>
</tr>
<tr>
<td>Overdenture</td>
<td>Acrylic resin</td>
<td>2,700</td>
<td>0.3</td>
</tr>
</tbody>
</table>

*According to manufacturer
MPa: Mega Pascal
RESULTS

Stress distribution in peri-implant bone

The analysis revealed comparable maximum von Mises stress in the peri-implant bone between titanium and zirconia implants under vertical and oblique loads. With vertical load, the maximum von Mises stress values were 4.43 MPa and 3.92 MPa for zirconia and titanium implants respectively (Table 2.2). While under oblique load the recorded von Mises stress values were 2.82 MPa for the zirconia implants with corresponding value of 3.18 MPa for titanium implants (Table 2.2).

The distribution of von Mises stress in the bone-implant interface around titanium implant is shown in Figure 2.6. Under vertical loading, the von Mises stress was most evident around the apex of the most distal implant on the loaded side (Fig 2.6a). In the case of the oblique loading von Mises stress was located distally at the bone-implant interface around the neck of
the most distal implant on the loaded side (Fig 2.6b). Similar stress distribution was observed in the bone-implant interface around zirconia implants (Fig 2.7a, b).

Table 2.2 von Mises stress in peri-implant bone

<table>
<thead>
<tr>
<th>Dental implant</th>
<th>Von Misses Stresses in peri-implant bone (MPa) under vertical and oblique load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RP imp</td>
</tr>
<tr>
<td>Posterior</td>
<td></td>
</tr>
<tr>
<td>vertical</td>
<td>Y-TZP</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Posterior</td>
<td></td>
</tr>
<tr>
<td>oblique</td>
<td>Y-TZP</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

RP imp: Right posterior implant  
LP imp: Left posterior implant  
RA imp: Right anterior implant  
LA imp: Left anterior implant

Figure 2.6a Bone cylinder showing Von Mises stress distribution in the peri-implant bone under vertical load in Ti implants
Figure 2.6b Bone cylinder showing Von Mises stress distribution in the peri-implant bone under oblique load in Ti implants.

Figure 2.7a Bone cylinder showing Von Mises stress distribution in the peri-implant bone under vertical load in Zirconia implants
Figure 2.7b Bone cylinder showing Von Mises stress distribution in the peri-implant bone under oblique load in Zirconia implants.

Strain Distribution in Peri-Implant Bone

The general pattern of the strain distribution was similar to that of the von Mises stress distribution (Table 2.3). Under the vertical load, the maximal strain value was observed at the bone-implant interface around apex of the implant with the values of 2823 microstrain (µε) and 2497 µε for zirconia and titanium implants respectively. With the oblique load, there was a shift in maximum strain values to the bone-implant interface around the neck of the most distal implant on the loaded side for both zirconia (1799 µε) and titanium (2027 µε) implants.

Table 2.3 Strain in peri-implant bone under vertical and oblique load

<table>
<thead>
<tr>
<th>Dental implant</th>
<th>Strain values (x10^-3) in peri-implant bone under vertical and oblique load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RP imp</td>
</tr>
<tr>
<td>Posterior vertical</td>
<td>Y-TZP</td>
</tr>
<tr>
<td></td>
<td>Ti</td>
</tr>
<tr>
<td>Posterior oblique</td>
<td>Y-TZP</td>
</tr>
<tr>
<td></td>
<td>Ti</td>
</tr>
</tbody>
</table>

RP imp: Right posterior implant
LP imp: Left posterior implant
RA imp: Right anterior implant
LA imp: Left anterior implant
Stress Distribution in Implants

First principal stress recorded on titanium and zirconia implants is given in Table 2.4. For the titanium implants, the maximum stress values were 22.68 MPa and 87.7 MPa under vertical and oblique load respectively. Under both loading conditions, the maximum stresses were mainly located disto-buccally at the neck region of the most distal implant on the loaded side (Fig 2.8). There was a slight variation in the tensile stress distribution patterns between two loading conditions. Under axial load, the maximum stress was mainly evident at the neck region with no apical extension along the implant body (Fig 2.8a). On the other hand, under oblique loading, the highest stress was concentrated at the neck region of the implant and gradually decreasing apically and disappearing completely at the level of the fifth thread (Fig 2.8b). A similar pattern of stress distribution was observed for the zirconia implants showing 22.85 MPa and 87.99 MPa under vertical and oblique load respectively (Table 2.4). However, under oblique loading, the stress extended more apically for the zirconia implants (Fig 2.9).

Table 2.4 First Principal Stresses in Implants (MPa)

<table>
<thead>
<tr>
<th>Dental implant</th>
<th>RP imp</th>
<th>LP imp</th>
<th>RA imp</th>
<th>LA imp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Posterior vertical Y-TZP Ti</td>
<td>22.85</td>
<td>6.36</td>
<td>11.3</td>
<td>6.37</td>
</tr>
<tr>
<td>Posterior oblique Y-TZP Ti</td>
<td>87.99</td>
<td>42.64</td>
<td>80.68</td>
<td>69.38</td>
</tr>
</tbody>
</table>

RP imp: Right posterior implant
LP imp: Left posterior implant
RA imp: Right anterior implant
LA imp: Left anterior implant
Figure 2.8a First principal stress in Ti implants under vertical load

Figure 2.8b First principal stress in Ti implants under oblique load
Figure 2.9a First principal stress in Zirconia implants under vertical load

Figure 2.9b First principal stress in Zirconia implants under oblique load

DISCUSSION

The aim of this finite element analysis (3D-FEA) was to compare the computerized biomechanical behavior of commercially pure titanium and Y-TZP oral implants placed in an edentulous maxilla to support overdentures. Finite element analysis (FEA) has been widely used in biomedical fields, especially for assessing stresses and strains in oral implants and the
surrounding structures (Geng et al., 2001). The von Mises and principal stress (tensile and compressive) values have been used to assess the stresses observed in the bone-implant interfaces along the long axes of the loaded implants. Von Mises stress values are defined as the effect of 3 principal stress components in a unique value, which is indicative of the onset of a distortional stress state in a body, and has been used to interpret the critical stresses within the peri-implant bone (Shinya et al., 2011). For the implants first principal stresses (the maximum tensile values) were considered to be more appropriate because failure occurs when the tensile stresses are greater than or equal to the ultimate tensile strength of the material (Choi et al., 2011; Shinya et al., 2011).

Acknowledging the brittle nature of ceramic implants it was considered more appropriate to use unsplinted implants with free standing attachment systems. Ball attachments allowed for free denture rotation during dorsal loading and twist-free load transmission to the implants in a nearly axial direction (Närhi et al., 2001; Van Steenberghe et al., 2001). This is seen to possibly protect against implant overloading (stress-breaking function) because of more force transmission being transferred to the posterior residual ridge (Närhi et al., 2001; Van Steenberghe et al., 2001).

Materials used for fabrication of endosseous dental implants can be categorized according to their chemical composition into metals, ceramics or polymers. Metals, with the emphasis on titanium and its alloys, have been the preferred materials and are expected to remain so on the long-term (González & Mirza-Rosca, 1999). Numerous investigations have demonstrated the reliability of this material for both mid-and long-term use. However, increasing number of studies reporting titanium allergy highlights the importance of search for an alternative implant material such as Y-TZP (du Preez et al., 2007; Egusa et al., 2008; Sicilia et al., 2008). Zirconia as a ceramic oxide, exhibits superior corrosion and wear resistance. Considering that oxides are the highest oxidation state of the metal, zirconia is highly stable in the most invasive biomedical environment and thus represents an appropriate alternative material in cases of titanium allergy (Black & Hastings, 1998).

A number of 3D-FEA studies have compared loading response between zirconia and titanium implants (Kohal et al., 2002; Çağlar et al., 2010, 2011; Choi et al., 2012). However, most of them were on single implants in the anterior maxilla and modeled on solid cortical and cancellous bone in uncomplicated anatomical and geometric configurations. These studies revealed comparable or even lower stress distribution in the surrounding bone when
Zirconia implants were used (Kohal et al., 2002; Çağlar et al., 2011) Another study, which evaluated stresses occurring on three different zirconia oral implants and peri-implant bone, concluded that different implant body and thread designs may affect the different stress patterns (Çağlar et al., 2010). Choi et al. (2012) compared the stress pattern between Ti-6Al-4V and PS-ZrO₂ implants during clenching in a posterior mandibular model and found high stress magnitudes on oral implants and the surrounding osseous structures. These stresses were not clinically critical since the mechanical properties of implants and bone can withstand stress values far greater than those recorded in their analysis.

The results of the previously mentioned studies cannot be directly extrapolated for comparison with those of the current analysis due to the difference in the number, design and distribution of implants as well as type of superstructure used. However, general trend can be seen. In accordance with the previous studies, similar pattern of stress distribution for both implant materials suggest that biomechanically zirconia implants may be a potential alternative to titanium implants for support of overdentures. There has been no report of 3D-FEA comparing zirconia and titanium implants supporting maxillary overdentures.

For both implant materials under axial load, maximum von Mises stress was located at the bone-implant interface around the apex of the implant while with the oblique load the maximum stress was transferred to the peri-implant bone around the neck of the implant. In the absence of stiff cortical bone from the alveolar region to sustain and resist the implant compression under the axial load, high stress was transmitted to the peri-implant bone between implant apex and stiff sinus floor. On the other hand, under the buccolinguinal load the implant deflected transmitting the maximum load to the bone-implant interface around the neck of the implant (Okumura et al., 2010). Furthermore, the hollow supporting structures of the maxilla and skull (sinus and nasal cavities) limit the sufficient apical bulk of supporting bone above the implants to resist the axial loading force from radiating inward along the implant towards its apical third (Gross et al., 2001). Despite the difference in the bending behavior given by the different modulus of elasticity of two implant materials, minimal difference was observed in stress values in peri-implant bone. This finding may be attributed to the fact that the implant materials are far stiffer than the surrounding cancellous bone. Thus the implants tend to be more displaced and less deformed under load with a consequently less influence of different elastic modulus of the implant materials on the bone stress values (Okumura et al., 2010). This might suggest that in the presence of stiff cortical bone in the
alveolar ridge region different stress levels might be observed between the two different materials, an aspect that is worth exploring in a future study.

Stresses recorded on titanium and zirconia implants were not clinically significant as the mechanical properties of implant material could withstand stress magnitudes far greater than those recorded in this analysis. Grade IV Cp-Ti can tolerate stress of up to 500 MPa without irreversible deformation (Koca et al., 2005). Therefore, the stress values of 87.7 MPa (oblique load) and 22.68 MPa (vertical load) generated in this study are unlikely to cause mechanical failure. In the case of zirconia implants, the maximum tensile stress values under both vertical (22.85 MPa) and oblique load (87.9 MPa) were well-below the flexural strength of zirconia (700–800 MPa). Zirconia implants exhibited more apical distribution of stresses compared to titanium under the oblique load. This may be attributed to higher modulus of elasticity of zirconia implants used in this study. Clinically, the wide spread distribution of tensile stresses along implant body may result in a more favorable physiological biomechanical environment for the bone with less force transmitted to the bone-implant interface. The comparable stress values for both implant materials was logical and expected considering that the two materials involved have Young’s modulus within a close range (Ti ≈ 104 GPa; YPSZ ≈ 220 GPa) (Kohal et al., 2002). A previous study has shown that unless the difference in Young modulus among tested material is greater than five-to-sevenfold, minimal difference in stress levels and variations will be observed (Kampiosiora et al., 1994).

According to Wolf’s law, mechanical load in the bone environment has been proposed as a possible stimulus that governs adaptive bone response (Frost, 2001). The absolute values of equivalent strains experienced in the bone adjacent to the zirconia implants of 2823 µε and 1799 µε under both vertical and oblique loads, respectively, and the corresponding values for the titanium implants of 2497 µε and 2027 µε are in the physiological remodeling range for bone according to Wolf’s law. Under vertical load, titanium implants showed approximately 10% less equivalent strain value compared to zirconia implants, whereas the reverse occurred under oblique load. This can be explained on the basis of the difference in the modulus of elasticity between the two materials. Under the oblique load and in the absence of stiff cortical bone, the less rigid titanium implant tends to be more deflected compared to the stiffer zirconia implant, thus transmitting greater stresses and higher strain to the peri-implant bone around the neck of the implant. On the other hand, under axial loading, the titanium implants tend to be more compressed transmitting some of the loads to the surrounding mucosal tissue and less load to the apical tissue.
The excellent strength, superior fracture resistance as a result of the inherent transformation toughening mechanism, enhanced biocompatibility, the low radioactivity and the esthetic properties of zirconia (Y-TZP) suggest that it can be a potential alternative for commercially pure titanium oral implants (Vagkopoulou et al., 2009). In the present study, the comparable stress/strain values observed between the two implant materials suggest that zirconia implants can be used as an alternative to titanium oral implants to support maxillary overdentures. Favourable soft tissue outcome achieved with zirconia abutments in the rehabilitation of partially dentate cases (Rimondini et al., 2002; Scarano et al., 2004) could also be appealing for implant overdenture cases where soft tissue complications are a frequently encountered problem (Jemt et al., 1992; Johns et al., 1992; Payne et al., 2001b). However, prospective clinical studies are still required to confirm these in-vitro results.

CONCLUSIONS

Within the limitations of the present study, the patterns of stress distribution of zirconia and titanium implants supporting maxillary overdentures were similar. This suggests that zirconia implants may be a potential alternative to titanium implants for overdenture support. This is particularly relevant for patients with allergy to titanium or those requesting metal-free restorations. Bone quality and implant design play a major role in the pattern of stress distribution and should be more thoroughly investigated and considered during treatment planning. Furthermore, prospective clinical trials are also required to confirm these in-vitro results and allow a better understanding of the biomechanics of zirconia implants.
CHAPTER II

In-vitro finite element analysis studies to validate research question

PART 2: A Finite Element Analysis of a Novel Implant Distribution Supporting Maxillary Overdentures

Publication status: Published

ABSTRACT

To evaluate the biomechanics of novel implant distributions and compare it with that of conventional maxillary overdenture support using a three-dimensional finite element analysis (FEA). The application of ceramic implants in the context of this novel design was also evaluated. Detailed FEA models were created to analyze the loading response of three different implant distributions supporting maxillary overdentures. The three implant design configurations were as follows: (D1) four unsplinted implants in the premolar regions; (D2) one mid-palatal implant, two bilateral canine/premolar implants and one off-center crestal implant; (D3) two bilateral canine/premolar implants, one incisive canal implant and one mid-palatal implant. Anatomical sites were modeled from computerized tomographic data and static loads were applied axially and obliquely. Von Mises stresses and equivalent strains generated in peri-implant bone and first principal stresses in the implants were calculated as well as denture displacements. Comparable stress and strain values were shown in the peri-implant bone for the three designs. A significant decrease in the first principal stresses of D2 implants was observed with the oblique load compared with D1 and D3. However, D3 design showed a shift of maximum stresses from vulnerable neck region to the higher strength transmucosal collar region of the implant. The maximum equivalent strain produced in the peri-implant region was mostly within the range for bone augmentation. D2 displayed the lowest maximum displacement values of the three designs. Maximum tensile stresses developed in the ceramic implants for the three designs were well below their fracture strength. The novel quad designs involving a mid-palatal and crestal implants or incisive canal, mid-palatal and crestal implants may be a potential alternative to that of conventional design used for maxillary overdentures. This is particularly relevant where anatomical considerations prevent a minimum of four anterior crestal implants. Ceramic implants may also be a valid option for a selected group of patients or for those requesting metal-free restorations. Prospective clinical studies are still required to confirm these in-vitro results.
Implant overdentures have significantly improved the quality of life for completely edentulous patients by providing better retention and support for the removable prostheses resulting in an improved chewing efficiency. However, the literature has reported considerably lower success rates for maxillary implant overdentures compared to their mandibular counterparts particularly due to the biological limitations of compromised bone quantity and quality of maxilla as well as unplanned treatment occurring when fixed prosthesis option becomes obsolete (Engquist et al., 1988; Jemt et al., 1992; Palmqvist et al., 1994; Ekdeldt et al., 2001; Widbom et al., 2005). From a biomechanical perspective, the number of implants and their distribution should be controlled to overcome these limitations by improving the loading conditions and consequently the implant success rates and prosthodontic treatment outcome (Brunski et al., 2000; Mericske-Stern et al., 2000b; Geng et al., 2001; Eckert & Carr, 2004; Krennmaier et al., 2008).

Unfavorable bending moments must be avoided by placing maximum number of implants widely distributed within the edentulous arch (Kramer et al., 1992; Glantz & Nilner, 1998; Mericske-Stern et al., 2000b; Eckert & Carr, 2004). Unfortunately, morpho-anatomic considerations often dictate a reduced implant number that is concentrated in the canine/premolar region and hence in the most compromised area from a biomechanical perspective (Chan et al., 1998; Henry, 2002; Sadowsky, 2007). Therefore, to reduce potentially high stress-strain fields at the bone-implant interface, a number of alternatives have been suggested. The use of longer and wider implants is one option (Duyck & Naert, 1997; Meyer et al., 2001; Himmlová et al., 2004; Baggi et al., 2008; Li et al., 2009) as well as tilted implant placement along the anterior sinus wall (Aparicio et al., 2001; Calandriello & Tomatis, 2005; Bellini et al., 2009). Augmentation of the intended implant sites using grafting or sinus lift techniques has also been explored (Baggi et al., 2008). Nevertheless, these additional surgical procedures can often be invasive and less predictable (Kahnberg et al., 2001), thus exploring an alternative implant site is a critical requirement.

Buttress implants such as zygomatic (Aparicio et al., 2006) and pterygoid implants Peñarrocha et al., 2009b), mid-palatal (Machado et al., 2008) and nasopalatine implants (Scher, 1994) are examples of alternative implant sites. The mid-palatal implant is of particular interest based on high success and survival rates reported with palatal orthodontic implants. Of particular interest is the pattern of loading, being subjected to occlusal forces
which are discontinuous and mainly parallel to the long axis of the implants (Männchen & Schätzle, 2008). Designs combining a mid-palatal implant with crestal implants or mid-palatal implant with crestal and incisive canal implants may result in an increased number of fulcrum lines and load sharing sites. In addition to using resilient attachment systems, a decrease in bending moment at the loaded side and therefore, reducing the risk of mechanical overloading for the distal implants may be achieved including more even load sharing between the loaded and contralateral sides (Duyck & Naert, 1997; Eckert & Carr, 2004).

Amongst the other related implant parameters, implant material selection plays a key role for the success of implant treatment (Sykaras et al., 2000; Geng et al., 2001). Recently, ceramic implants have been increasingly used for the rehabilitation of partially dentate patients showing favorable outcomes compared to titanium implants (Akagwa et al., 1998; Kohal et al., 2002; Kohal & Klaus, 2004; Kohal et al., 2004; Bächle et al., 2007; Hoffmann et al., 2008; Oliva et al., 2007; Oliva et al., 2008a; Pirker & Kocher, 2008; Andreiotelli & Kohal, 2009; Kohal et al., 2009a). One FEA study comparing the stress distribution pattern between zirconia (Y-TZP) and titanium implants supporting single crowns showed comparable stress distribution patterns with zirconia implants (Kohal et al., 2002). Despite all these findings, no study up-to-date has considered the use of ceramic implants in the overdenture field.

Therefore, this study will evaluate the biomechanics of novel implant distributions compared to the conventionally used design for supporting a maxillary overdenture. The application of ceramic implants in the context of these novel designs will also be examined.

MATERIALS AND METHODS

A three-dimensional finite element analysis (3-D FEA) model of an edentulous maxilla restored with an implant overdenture was simulated using Cosmosworks 2007 (Solid Works Corporation UK). Three different implant distributions were investigated. In the first design (D1) four implants (Ø3.8 mm x 11.5 mm) were placed bilaterally in the canine/premolar region (Fig 2.10a). The second design (D2) included an off-center crestal implant (Ø3.8 mm x 11.5 mm), two bilateral implants in the premolar region (Ø3.8 mm x 11.5 mm), and a mid-palatal implant (Ø6 mm x 5 mm) posterior to the two distal implants (Fig 2.10b). For the third design (D3) the implants distribution was as follows 2 bilateral canine/premolar implants (Ø3.8 mm x 11.5 mm), one incisive canal implant (Ø7 mm x 10 mm) and one mid-palatal
implant (Ø 6 mm x 5 mm) (Fig 2.10c). In both D2 and D3 the mid-palatal implant was posterior to the two distal implants resulting in a diamond-shape distribution (quad design).

Figure 2.10 Three models simulated (a) D1, (b) D2 and (c) D3.
The maxillary model used in the FEA was derived from a series of axial sections of computerized tomography scan images (CT) of a completely edentulous maxilla. The mucosal layer was designed with varying thickness to simulate a more realistic clinical situation (Cheng et al., 2010). For this analysis, a dense fine trabecular bone with no cortical layer was assumed to better represent the actual clinical situation. Maxillary models that have a cancellous core with mechanical properties of magnitude less than that of the overlying cortical layer may behave as if the implants are only supported by the cortical bone (Saab et al., 2007). Most of the force would be supported by the cortical bone and the reaction force within the cancellous bone underestimated (Clelland et al., 1993; Saab et al., 2007). The implants and attachments were modeled according to the specifications provided by the manufacturer (Southern Implants, Irene, South Africa). The overdenture was designed to provide a complete palatal coverage. The average prosthesis height was 15 mm. The nylon caps were incorporated on the intaglio surface of the overdentures with the additional thickness of 2mm of acrylic covering the housings.

The models were meshed with 3-D parabolic tetrahedral solid elements with surface-to-surface contact to produce a high quality solid mesh. The total number of elements and nodes are summarized in Table 2.5. The average element size used was 0.9 mm with 0.045 mm tolerance. The border between the implant and the maxillary bone was fine meshed at the edges to ensure accuracy of the analysis. All the materials were presumed to be linear, elastic, homogenous and isotropic with corresponding elastic properties such as Young’s modulus and Poisson’s ratio determined from the literature (Geng et al., 2001) (Table 2.6). The material properties of zirconia implants and attachment systems were provided by the manufacturer (Southern Implants, Irene, South Africa). A fixed bond between the implants and bone was assumed to simulate 100% osseointegration. The overdenture and plastic attachments were allowed to move freely on top of implants and mucosa by defining a no penetration sliding contact at the interfaces with a friction coefficient of 0.3 (Chun et al., 2005; Saab et al., 2007). The simulated elastic properties of the cap attachment allowed for its compression during the loading of the overdenture. Furthermore, the lack of contact between the side walls of the nylon cap and the implant neck in addition to the space created between flat top of ball abutment and its corresponding recess in plastic cap allowed the free movement of nylon cap over the ball surface during loading vertically and to a limited extent laterally.
The entire assembly was restrained at the superior aspect of the maxilla to avoid total body displacement under load (Saab et al., 2007). Static loads of 300 N (75 N per premolar and 150 N for the first molar) were applied axially on the fossa of acrylic denture teeth and 20° buccolingually on the buccal slope of the lingual cusps of posterior teeth of the first quadrant. For further information on the methodology the reader is referred to the first part of this chapter.

Finite element iterative solver software (FFE plus solver) was used to compute von Mises stresses and equivalent strains in the bone, first principal stresses in the implants and displacement of denture in each model. The numerical data were color coded and compared between the models.

<table>
<thead>
<tr>
<th>Table 2.5 Elements and Nodes of Three Models</th>
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<tr>
<td><strong>Elements</strong></td>
</tr>
<tr>
<td>Design1</td>
</tr>
<tr>
<td>Design2</td>
</tr>
<tr>
<td>Design 3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2.6 Assumptions for the Finite Element Analysis (FEA) Model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Component</strong></td>
</tr>
<tr>
<td>Maxillary bone</td>
</tr>
<tr>
<td>Mucosal layer</td>
</tr>
<tr>
<td>Implant*</td>
</tr>
<tr>
<td>Plastic cap*</td>
</tr>
<tr>
<td>Overdenture</td>
</tr>
</tbody>
</table>

*According to manufacturer

MPa: Mega Pascal

**RESULTS**

Stress Distribution in Peri-Implant Bone

Comparable von Mises stress values were observed in the peri-implant bone of three designs under both vertical and oblique loads. With vertical load, the highest von Mises stress values 4.58 MPa for D1, 6.83 MPa for D2 and 5.9 MPa for D3 were concentrated at the bone-
implant interface around the apex of the most distal implant on the loaded side (Fig 2.11 and Table 2.7). For D1, under oblique load, the highest von-Mises stress values were found at bone-implant interface around the neck of the most distal implant on the loaded side (Fig 2.12 and Table 2.7), while for D2 and D3 there was a shift in maximum stresses to the peri-implant bone around the neck of the mid-palatal implant and incisive canal implant respectively (Fig 2.12 and Table 2.7).

Figure 2.11 Von Mises stress distribution in the peri-implant bone under vertical load in (a) D1, (b) D2 and (c) D3.
Figure 2.12 Von Mises stresses in the peri-implant bone under oblique load in (a) D1, (b) D 2 and (c) D 3.
Strain Distribution in Peri-Implant Bone

The general pattern of the equivalent strain distribution was similar to that of the stress distribution. The values for the three designs under both the oblique and axial loads are summarized in Table 2.8. Under the axial load, the maximal strain values were observed in the bone around the apex of the most distal implant on the loaded side for D1, D2 and D3 with values of 2920 microstrain (µε), 4350 µε and 3760 µε respectively. For D1, with the oblique load, the same pattern of strain distribution was observed with a value of 2090 µε. While for the other 2 designs there was a shift in maximum strain values to the bone-implant interface around the neck of the mid-palatal implant for D2 and to the bone-implant interface around the neck of the incisive foramen implant for D3. The maximum strain values for D2 and D3 were 2110 µε and 2730 µε respectively.

Stress Distribution in Implants

For D1, D2 under the vertical load, the maximum principal tensile stress values were 27.4 MPa and 23.9 MPa respectively, located at the neck of the most distal implant on the loaded side (Fig 2.13a, 2.14 and Table 2.9). In the case of D3, the maximum principle tensile stress was shifted to the trans-mucosal collar of the incisive canal implant with a corresponding value of (45 MPa) (Fig 2.15a and Table 2.9). The same pattern of stress distribution was observed under the oblique load, however, with higher values for all designs with maximum principal tensile stress values of 106.8 MPa, 88.6 MPa and 132 MPa for D1, D2 and D3 respectively (Fig 2.13b, 2.15, 2.17a and Table 2.9).
Figure 2.13 Most distal implant on loaded side in D1 showing maximum tensile stress values under (a) vertical load and (b) oblique load.
Figure 2.14 First principal stresses in the implants under vertical load in D2 (a) on most distal implant on loaded side and (b) on mid-palatal implant.
**Figure 2.15** First principal stresses in the implants under oblique load in D 2 (a) on most distal implant on loaded side and (b) on mid-palatal implant
Figure 2.16 First principal stresses in the implants under vertical load in D3 (a) on incisive canal implant, (b) on mid-palatal implant and (c) on most distal implant on loaded side
Figure 2.17 First principal stresses in the implants under oblique load in D3 (a) on incisive canal implant, (b) on mid-palatal implant and (c) on most distal implant on loaded side
Displacement

Table 2.10 displays the maximum displacement values in the Y-direction under both the vertical and oblique loads. D2 and D3 showed markedly less displacement than D1 under both vertical and oblique loads (Fig 2.18, 2.19 and 2.20).

Figure 2.18 Denture displacement in Y-axis under (a) vertical load and (b) oblique load in D1.
Figure 2.19 Denture displacement in Y-axis under (a) vertical load and (b) oblique load in D2.
Figure 2.20 Denture displacement in Y-axis under (a) vertical load and (b) oblique load in D3.
### Table 2.7 Von Mises Stresses in Peri-implant Bone (MPa)

<table>
<thead>
<tr>
<th></th>
<th>RP imp</th>
<th>LP imp</th>
<th>RA imp</th>
<th>LA imp</th>
<th>Mid imp</th>
<th>MP imp</th>
<th>IC imp</th>
</tr>
</thead>
<tbody>
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<td><strong>Posterior Vertical</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design 1</td>
<td>4.58</td>
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<td>0.92</td>
<td>0.25</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>2.33</td>
<td>2.73</td>
</tr>
</tbody>
</table>

### Table 2.8 Strain Values ($x10^{-3}$) in Peri-implant Bone under Vertical and Oblique Loads

<table>
<thead>
<tr>
<th></th>
<th>RP imp</th>
<th>LP imp</th>
<th>RA imp</th>
<th>LA imp</th>
<th>Mid imp</th>
<th>MP imp</th>
<th>IC imp</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Design 1</td>
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<td>0.22</td>
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<td>0.16</td>
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</tr>
<tr>
<td>Design 2</td>
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<td>0.18</td>
<td>-</td>
<td>-</td>
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<tr>
<td><strong>Posterior Oblique</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td>-</td>
<td>-</td>
<td>1.74</td>
<td>2.73</td>
</tr>
</tbody>
</table>

**RP imp:** Right posterior implant  
**LP imp:** Left posterior implant  
**RA imp:** Right anterior implant  
**LA imp:** Left anterior implant  
**Mid imp:** Mid-crestal implant  
**MP imp:** Mid-palatal implant  
**IC imp:** Incisive canal implant
### Table 2.9 First Principal Stresses in Implants under Vertical and Oblique Loads (MPa)

<table>
<thead>
<tr>
<th>Posterior Vertical</th>
<th>RP imp</th>
<th>LP imp</th>
<th>RA imp</th>
<th>LA imp</th>
<th>Mid imp</th>
<th>MP imp</th>
<th>IC imp</th>
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<td>11.3</td>
<td>6.37</td>
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<td>45</td>
</tr>
<tr>
<td>Posterior Oblique</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
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<td>94.7</td>
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<td>2.56</td>
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<td>Design 3</td>
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<td>37</td>
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<td>-</td>
<td>-</td>
<td>79.5</td>
<td>132</td>
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### Table 2.10 Denture Displacement in Vertical Axis (Y-axis)

<table>
<thead>
<tr>
<th>Vertical Load</th>
<th>Vertical Load</th>
<th>Oblique Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum (µε)</td>
<td>Minimum (µε)</td>
<td>Maximum (µε)</td>
</tr>
<tr>
<td>Design 1</td>
<td>160</td>
<td>-130</td>
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<tr>
<td>Design 2</td>
<td>130</td>
<td>-120</td>
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<tr>
<td>Design 3</td>
<td>135</td>
<td>-71</td>
</tr>
</tbody>
</table>
DISCUSSION

This study evaluated the biomechanical behavior of novel implant distributions supporting a maxillary overdenture and compared it with the conventional design using the finite element analysis (FEA). Von Mises stress values are defined as the distortional stress state in a body and indicative of the onset of deformation for ductile materials, and have also been used to interpret the critical stresses within the peri-implant bone (Mellal et al., 2004). For the zirconia implants which are classified as brittle in an engineering sense; first principal tensile stresses were considered to be more appropriate. Strain values in the peri-implant bone were also calculated to give an insight into maxillary bone remodeling relative to Frost’s values (Stanford & Brand, 1999; Mellal et al., 2004).

For D1, under vertical and oblique loads the maximum von Mises stress values were predominantly at the most distal implants on the loaded side. This is in accordance with several previous studies (Meyer et al., 2001; Tanino et al., 2007; Bellini et al., 2009) and may be attributed to the denture rotation around a fulcrum line passing through the most posterior implants when distal occlusal forces are applied. In the case of novel designs there was a shift in maximum stress values from crestal implants to buttress implants, which may result in a more favorable biomechanical environment. In D2, the mid-palatal implant was found to have a substantial load bearing capacity role, particularly under oblique load, where the maximum stress values were shared between it and the most distal implant on the loaded side. While in the case of D3, the maximum load was shared by incisive canal and mid-palatal implants. Wider implants provide a larger surface contact with the bone and thus lowering the resultant interaction stresses and increasing the implant success/survival rates (Winkler et al., 2000; Renouard & Nisand, 2006). Furthermore, the better bone quality of the mid-palatal region may be an additional supporting factor for the recommendation of such a site. In this context, Machado et al. (2008) and Ambard (2009) reported some cases where palatal implants either in descending premaxilla or mid-palatal suture combined with canine/premolar implants were successfully used to provide adequate support and retention for maxillary overdentures.

According to Frost’s Mechanostat theory, bone remodeling is stimulated by a biomechanical feedback system dependent on the stress/strain levels in the supporting bone (Frost, 2001). The exact values are unknown but it is assumed that microstrain levels below 50-100 με would result in bone loss known as disuse atrophy while values above 4000 με would result in pathological overload and irreversible bone damage (Frost, 1992; 2004). In
between exists two additional zones: a normal load (lazy zone) which covers the strain range between disuse (100 µε) to mild overload (1500 µε), and the mild overload zone between 1500 µε to 4000 µε (Frost, 1992; 2004). However, these values should not be considered absolute but rather as indicative (Mellal et al., 2004).

In the present study, with exception of the distal implant in D2 (4350 µε), all calculated maximum strain values within the bone adjacent to the implants on the loaded side were between 1900 µε and 3760 µε, which is in the remodeling zone of bone. Nevertheless, the high strain value (4350 µε) according to Frost’s theory could still be considered within the normal range, which ranges from 3400 to 6600 µε as reported by Melsen & Lang (2001). For the unloaded side, low microstrain values occurred which was in the disuse atrophy zone. However, in reality, patients would be biting on multiple sites rather than the load being concentrated unilaterally as seen in the current simulation.

The observation of comparable stress/strain values of three designs suggests that in the future the novel designs may become a potential alternative to the conventional design. This is particularly relevant when anatomical limitations preclude a minimum of four implants along the maxillary ridge, thus potentially eliminating the need for invasive surgical augmentation procedures.

A minimum of 4 implants in the quad design compared to a reduced implant number in the atrophic maxilla allows for a partly opened palatal design. This may be perceived as advantageous to patients by providing greater comfort through reduction of tissue coverage for complete denture wearers (Ochiai et al., 2004).

Clinically, an issue of concern with the novel designs would be the increased thickness of palatal vault that would be expected to adversely affect the patients’ phonetics. However the patient’s adaptive increase in the closest speaking space that occurs in such a circumstance could compensate for such a complication. This, result from an oro-sensory feedback which would provoke a more posterior positioning of the tongue, causing as in the case of macroglossia, a narrowing of the faring-tracheal diameter forcing the patient to increase the size of his mouth opening (Schierano et al., 2001). Verification of this outcome may be assessed by the use of diagnostic dentures with a thickened palatal vault to determine the patients’ adaptation which if proven to be problematic would be a contraindication to such a design.
In the case of using zirconia implants, the maximum tensile stress values under both vertical (27.4 MPa/23.9 MPa/45 MPa) and oblique load (106.8 MPa/88.6 MPa/132 MPa) in D1/D2/ D3 designs were well below the flexural strength of zirconia (700 – 800 MPa). These low values may in part arise from the low rigidity of the cancellous bone within which the implants are placed. There was an obvious decrease in first principal stress values within the implants seen with D2 compared to D1 and D3 under oblique loading. Nevertheless, an advantage seen in the case of D3 design was the shift of maximum stresses from the vulnerable neck region to the higher strength trans-mucosal collar of the implant. This may suggest more favorable biomechanics of this design in terms of implant loading. For all the three designs, the stress values were far beyond the critical values which emphasize and support the potential use of zirconia implants in the overdenture field particularly with the proposed novel implant distributions.

The possible application of zirconia implants in the overdenture field would address the increasing concerns regarding titanium hypersensitivity and its possible correlation to implant failure in susceptible patients with metal allergy (Siddiqi et al., 2011). However, due to manufacturing limitations related to inherent properties of zirconia it can be only be provided as a one-piece implant opposed to its titanium counterpart (Kohal et al., 2009b). In addition, it may satisfy the clinical demand of an increasing number of patients requesting metal-free restorations (Müller & Valentine-Thon, 2006; Egusa et al., 2008; Sicilia et al., 2008). The favourable soft tissue outcome achieved with zirconia abutments in the rehabilitation of partially edentulous cases (Rimondini et al., 2002; Scarano et al., 2004) could also be appealing when considered for implant overdenture patients where soft tissue complications are a frequently encountered problem (Jemt et al., 1992; Johns et al., 1992; Payne et al., 2001b).

The denture displacement generated during loading indicates lower displacement values in D2 and D3 compared to D1 (Table 2.10). This decreased denture movement may indicate reduced sliding contact of the attachment systems against the ball abutments, thus resulting in minimal wear of the patrices and consequently reduced maintenance requirements and improved patients’ satisfaction.

The finite element modeling technique used in the present study has some limitations. A simplified condition of 100% osseointegration between implants and bone was assumed.
Stress analysis was performed using a static load and the mechanical behavior of bone was modeled as isotropic and linearly elastic. These assumptions, therefore, do not demonstrate an actual clinical situation (Geng et al., 2001; Van Staden et al., 2006). Nevertheless, the results provide an overall insight on the influence of several variables on stress and strain patterns that support significant and clinically useful indications for both the novel placement and selection of ceramic implants.

**CONCLUSIONS**

The current study showed comparable stress and strain values between the conventional and the proposed novel implant distributions. The novel distributions, involving either a mid-palatal and incisive canal implants or a mid-palatal and crestal, may therefore be a potential alternative to that of the conventional design used for maxillary overdentures, particularly where anatomical considerations prevent a minimum of four anterior crestal implants. Ceramic implants showing encouraging FEA results also indicate that these may be a valid option for a selected group of patients or for those requesting metal-free restorations. Prospective clinical studies, however, are still required to confirm these in-vitro results.
CHAPTER III

A clinical pilot study investigating the application of zirconia implants for the support of overdentures

Zirconia Implants Supporting Overdentures: A Pilot Study with Novel Prosthodontic Designs

Publication status: In Press

The aim of this study was to present prosthodontic perspectives of novel designs used for zirconia implants supporting maxillary and mandibular implant overdentures with outcomes of a pilot study. Four pilot study participants (2 males and 2 females; mean age 59.8 years) for a planned clinical trial on zirconia implants supporting maxillary and mandibular overdentures at School of Dentistry, University of Otago, New Zealand were treated with novel designs for maxillary 4-implant overdentures (quadrilateral design) and mandibular 3-implant overdentures (tripodal design). A total of 28 implants were inserted: 16 in the maxilla and 12 in the mandible. Two implants in the mandible and 2 in the maxilla (14%) failed to achieve osseointegration prior to loading. In one participant with the failed mid-palatal implant, the incisive canal implant was also placed too deeply and hence the maxillary overdenture was supported by only the 2 crestal premolar region implants. The participant in whom the incisive canal foramen implant failed declined a replacement implant and the maxillary overdenture was supported using the remaining 3 implants. The participants with failed mandibular implants had them both replaced successfully. At the 1-year follow-up appointment, all the implants in the 4 participants were surviving and the overdentures were in function without any signs of wear of the matrices. This pilot study showed prosthodontic perspectives of a novel design used for zirconia implants supporting maxillary and mandibular implant overdentures. Preliminary outcomes indicate caution with regard to these proposed alternative implant sites and of the suitability of one-piece zirconia implants before accepting these novel prosthodontic designs for routine clinical practice.
INTRODUCTION

Treatment approaches have rarely addressed resolving the edentulous predicament using implant overdentures in both jaws (Zarb, 1983; Mericske-Stern & Taylor, 2000). The primary aim of implant overdentures is to provide edentulous patients with improved retention and stability of their prostheses, a better quality of life and minimize prosthodontic maintenance issues. Current shifts in treatment options towards zirconia implants will include edentulous patients who may be sensitive to titanium oral implants and metallic attachment systems (Wenz et al., 2008; Siddiqi et al., 2011).

Implant overdenture designs involve various implant distributions and attachment systems with significant variation between prosthodontic designs used for completely edentulous maxilla and mandible. More often than not, 2 splinted or unsplinted inter-foraminal implants are recommended to rehabilitate the edentulous mandible (Feine et al., 2002). Additional usage of posterior mandibular implants is rare. Frequently addressing the problems of single complete maxillary dentures opposing natural teeth, a minimum of 4 implants, independent of attachment system used, are usually advocated for maxillary overdentures (Sadowsky, 2007). More implants are recommended in compromised clinical situations; however, no widespread consensus on implant numbers, distribution and attachment system are found. Prosthodontic designs for maxillary overdentures are more challenging and complicated by the resorptive pattern of the maxilla and related anatomical considerations. Ideally, widely distributed implants spanning the anterior, the premolar regions and the tuberosities would allow the most favorable load distribution.

More significant interventions have been proposed for the reconstruction of severely atrophic maxillae but these interventions also present marked challenges to both surgeon and prosthodontist and commit the patient to traumatic surgery. More conservative approaches for implant positioning using alternative sites in the mid-palatal or incisal foramen area have also been explored (Scher, 1994; Männchen & Schätzle, 2008; Machado et al., 2008; Penárrocha et al., 2009a).

The aim of this research is to present the outcomes of a pilot study using a novel design for zirconia implants supporting maxillary and mandibular implant overdentures.
MATERIALS AND METHODS

The novel design

A maxillary quadrilateral design proposed involves 4 oral implants: a mid-palatal, incisive foramen, and bilateral premolar region implants (Fig 3.1a). The rationale is to have implant positions in both primary stress bearing area and secondary stress bearing areas of the edentulous maxilla (Jacobson & Krol, 1983c). Following the biomechanical principles applied for removable partial prosthodontics, the quadrilateral design will result in more fulcrum lines (Carr et al., 2005). The most anteriorly positioned implant depending on the force direction will act as an indirect retainer minimizing the tissue-ward movement of the prosthesis when occlusal dislodging forces are applied (Carr et al., 2005)(Fig 3.2). Reduced implant overdenture movement and stresses at bone-implant interfaces is anticipated.

A mandibular tripodal design proposed involves 3 oral implants: a single mid-symphysisal and bilateral distal implant in the molar areas (Fig 3.1b). Building on the historical philosophy of tripodization or staggered implant placement (Rangert et al., 1995), as well as acknowledging the current success of mandibular mid-symphysisal implants (Alsabeeha et al., 2011), two additional posterior implants would create a completely implant-supported overdenture. The positioning of these posterior implants creates a Kennedy III-type situation, as opposed to the more common approach of implant-and-mucosa supported overdenture being in a Kennedy I-type situation (Feine et al., 2002; Carr et al., 2005) (Fig 3.3). This tripod design may reduce posterior bone resorption and minimize prosthodontic maintenance of the attachment systems.

Prior to commencing a randomized clinical trial of the two prosthodontic designs, a pilot study involving four participants (two males and two females; mean age 59.8 years) was conducted at School of Dentistry, University of Otago, New Zealand. Ethical approval was obtained from the Lower South Ethics Committee (LRS/09/06/023). Participants who were smokers or medically compromised were excluded. Preoperative panoramic, lateral cephalometric and axial cross-sectional tomograms were taken to ensure sufficient amount of bone for implant placement at the proposed sites. Each participant received diagnostic complete dentures that were duplicated and used as a surgical guide.
Figure 3.1 Proposed (a) maxillary quadrilateral design and (b) mandibular tripodal design

Figure 3.2 Depending on the direction of forces the most anterior implant acts as an indirect retainer.

F<sub>a</sub>: Tissue away forces
IR: Indirect retention

Figure 3.3a Tissue-ward force results in distal rotation of prosthesis

F<sub>w</sub>: Tissue-ward force
FL: Fulcrum line

Figure 3.3b Tripod design eliminates distal rotation of prosthesis around anterior FL
Surgical procedures

Maxillary and mandibular one-piece zirconia implants with ball abutments (Southern Implants, Irene, South Africa) were placed at separate appointments by an experienced maxillofacial surgeon. The zirconia implants consisted of 95% zirconia with yttria and alumina making up the remaining 5%. The one-piece zirconia implants varied in diameter and length according to the site of implant placement. The diameter of maxillary crestal implants was 3.8 mm, whereas the incisive foramen and mid-palatal implant were either 5 or 7 mm. Mandibular implants had the diameters of either 5 or 7 mm with 3.1 or 3.5 mm ball abutments respectively. Both crestal and mid-palatal implants had a 2.25 mm diameter ball abutment. Both implants had the same thread configuration of a 0.6 mm pitch and a 0.1 mm width. The crestal implant had a 0.3 mm pitch depth, whereas the mid-palatal implant had a 0.5 mm depth. A midcrestal flap was raised for implant placement at all sites except for mid-palatal implant where a flapless technique was used. The distribution of implant lengths and diameters in the four participants are shown in Table 3.1.

Prosthodontic procedures

Immediately following surgery, the intaglio surfaces of existing complete dentures were relieved and relined with tissue conditioners (Visco-gel, Dentsply). After 4 months of healing (conventional loading protocol), a closed-mouth impression was made with polyether material (Impregum™ Penta™, 3M ESPE) for indirect relines to include custom-made matrices on the intaglio surface of the overdentures. The attachment systems comprised ball abutments (patrices) with different sizes including 2.25mm, 3.1mm and 3.95mm in diameter and their corresponding matrices. For the small abutments (2.25mm) the plastic matrix used were enclosed in a metal housing for the mechanical retention in the denture resin, while for the larger abutments only plastic clips were employed. Different diameters used are described in table 3.1. Participants were followed for one year (Fig 3.4).
<table>
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<tr>
<th>Participant</th>
<th>Maxilla</th>
<th>Mandible</th>
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<td>Implant Site</td>
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<td>3.8mmØ 11.5mm BallØ:2.25mm</td>
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<td>4</td>
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RESULTS

A total of 28 implants were inserted: 16 of these were placed in the maxilla with the quadrilateral design and 12 in the mandible with the tripodal design. Two implants in the mandible and two in the maxilla failed to achieve osseointegration prior to loading. In one participant with the failed mid-palatal implant, the incisive foramen implant was placed too deep and the maxillary overdenture was supported by only the 2 crestal premolar region implants. The participant, in whom the incisive foramen implant failed, declined a replacement implant and the maxillary overdenture was retained using the remaining 3 implants. The participants with failed mandibular implants had them replaced successfully prior to rehabilitation. At the 1-year follow-up, all the remaining and replaced implants in all four participants were surviving and the overdentures were functional without any signs of wear of the matrices. The only prosthodontic maintenance encountered was the constant need for the excision of hyperplastic mucosa surrounding the incisive foramen implant. The hyperplastic tissue had to be excised on four different occasions, twice for each of the surviving incisive foramen implants throughout the one-year follow-up period. The comfort
and stability, ability to speak, ease of cleaning, esthetics and function of prostheses were adequate as reported subjectively by participants.

**DISCUSSION**

The justification for using this novel prosthodontic design is based on the need for improved biomechanics when using one-piece zirconia implants for both maxillary and mandibular overdentures. Ideal anatomical locations for implant placement were identified that would theoretically reduce the fulcrum lines around which the prostheses rotate and thus minimize both residual ridge resorption and future prosthodontic maintenance. The feasibility of using novel sites for zirconia implant placement and satisfactory prosthodontic outcomes for maxillary and mandibular overdentures was proved via this pilot study for conducting a planned randomized clinical trial. Implant losses were attributed to design features of the prototype zirconia implants rather than the prosthodontic protocol.

For the mandibular overdentures, biomechanics could be influential on prosthodontic treatment outcomes and maintenance. The tripodal design in the mandible resulted in a very stable overdentures for the pilot participants. Although there is literature showing that prospective and retrospective studies on 2-versus 4-implant overdentures reveal comparable patient satisfaction levels, there is evidence for patient preference for mandibular 4-implant overdentures (Tang et al., 1997). It is acknowledged that as a limitation of this research, the placement of implants in the mandibular posterior region is technically more demanding due to the severe residual ridge resorption that may be encountered there.

The practicality of the alternative maxillary implant sites we have proposed deserves comments. Currently, little evidence exists for the long-term success and survival rates of implants placed in the mid palatal region; however, the encouraging results of this pilot study warrant more extensive examination of this anatomic site. Traditionally, the incisive foramen has been avoided due to concerns regarding damages to its neurovascular contents (Liang et al., 2009). However, the current pilot study found that the use of this site did not cause any discomfort or sensory disorder for the participants. Of greater concern was the need for the excision of hyperplastic peri-implant mucosa to expose the ball abutment head of the one-piece zirconia implants. In this pilot study, out of 4 implants in the incisive foramen, one implant failed and another became unfeasible due to the deep placement and hyperplastic peri-implant mucosa. Due to the prosthodontic rehabilitation difficulties, a modified quadrilateral design where the incisive foramen site is replaced by an off-centered anterior
A crestal implant is proposed. This design would retain the biomechanically-favorable distribution of forces seen in the initial design. Despite this, the preliminary findings of this study suggest that the incisive foramen can be used as an alternative implant site for the rehabilitation of the edentulous maxilla in selected cases when inadequate bone exists in the anterior maxillary alveolar ridge or in case of two-pieces implant where an increased length abutment can be selected.

To accommodate the attachment systems for the palatal and maxillary incisive foramen implants, the palate of the overdenture had to be thickened. Slight thickening of the maxillary palatal vault to avoid midline denture fracture did not adversely influence the speech as subjectively determined by the participants. This could be explained by an increase in closest speaking space that occurs with thickening resin palatal vault of complete dentures. It has been shown that regularity of the closest speaking space obtained 90 days after thickening the resin palatal vault of maxillary complete dentures can be interpreted as a sign of patients’ adaptation to the prosthesis (Schierano et al., 2001).

The limitations of this pilot study are acknowledged. They relate to the number of variables used to properly assess these novel designs. It is recognized that difficulties with prosthodontic rehabilitation are encountered when placing a one-piece implant in the incisive foramen, especially in the case of deep placement. In addition the thickness of oral mucosa could hinder the engagement of the attachment systems. As a result there is a need for modifications of the proposed designs to address some of the issues identified in this pilot study.

**CONCLUSIONS**

This present study constitutes proof-of-principle for prosthodontic perspectives of a novel design using one-piece zirconia implants to support maxillary and mandibular implant overdentures. The outcomes indicate caution with these proposed alternative implant sites; therefore, some modifications to the initial quadrilateral design are proposed. Further investigations of the suitability of one-piece zirconia implants are warranted before accepting these novel prosthodontic designs for routine clinical practice. This pilot study provides evidence for conducting a planned randomized controlled trial.
CHAPTER IV

Clinical and prosthodontic outcomes of ceramic implants supporting maxillary and mandibular overdentures

PART 1: Ceramic implants (Y-TZP): are they a viable alternative to titanium implants for the support of overdentures? A randomized Clinical Trial.

Publication status: Under Review

Osman, R.B., Duncan, W., Swain, M.V., Ateih, M., Ma, S. Ceramic implants (Y-TZP): are they a viable alternative to titanium implants for the support of overdentures? A randomized Clinical Trial. Clin Oral Implants Res; [Under Review].
ABSTRACT

To assess one-year clinical success of one-piece zirconia Y-TZP implants compared with titanium implants of the same design, in the context of a novel protocol for implant distribution. Twenty-four edentulous participants were randomly allocated to one-piece titanium or zirconia implant groups. Each participant received four implants in the maxilla (mid-palatal and three anterior crestal implants) and three implants in the mandible (mid-symphysisal and two bilateral distal implants). A conventional loading protocol was followed. Marginal bone remodeling and clinical success of implants were evaluated. The data was statistically analyzed using SPSS software and risk predictors for implant failures were evaluated. At the end of the observation period, 129 implants were available for analysis. There was no significant difference in the survival rate between the two groups in either jaw. In the mandible the survival rate of titanium implants was 95.8% versus 90.9% for the zirconia implants. The corresponding values in the maxilla were 71.9% and 55% respectively. Three implants in the zirconia group fractured. Less mean marginal bone loss was observed around titanium implants (0.18mm) compared to the zirconia group (0.42mm). The difference was statistically significant ($P<0.05$). The Prediction model for implant failure revealed that the implants placed in the maxilla were at the highest risk of failure ($P <0.0001$). The outcome of this study indicates caution before recommendation can be made for the use of single-piece zirconia implants for overdenture support. Their use should be limited to cases with proven allergy to titanium. This is mainly due to the increased bone loss and higher fracture rate observed for zirconia implants.
Ceramic materials for oral implants were first introduced and clinically used some 30-40 years ago (McKinney & Koth, 1982; Koth et al., 1988; Fartash et al., 1990; 1995; 1996; Arvidson et al., 1991; Berge & Grønning, 2000; Andreiotelli et al., 2009). Pioneer attempts involved the use of aluminum oxide (polycrystals or single crystal) endosseous implants for mandibular overdenture rehabilitation (Fartash et al., 1995; 1996; Berge & Grønning, 2000). Although sapphire implants met the biological and physical requirements for dental implants, the inferior mechanical properties and reduced survival rate of these systems compared to titanium implants led to their withdrawal from the market (Berge & Grønning, 2000; Kohal et al., 2008; Andreiotelli et al., 2009). Consequently, interest in ceramic implants decreased for a period, but has been renewed with the introduction of implants fabricated from zirconia, particularly those made of yttria-stabilized tetragonal zirconia polycrystals (Y-TZP) (Kohal et al., 2008; Wenz et al., 2008; Andreiotelli et al., 2009; Özkurt & Kazazoğlu, 2011).

Zirconia exhibits good physical and mechanical properties (Piconi & Maccauro, 1999; Denry & Kelly, 2008; Hisbergues et al., 2009). Compared with alumina, Y-TZP has a higher bending strength, a lower modulus of elasticity and higher fracture toughness. Stress-induced transformation toughening is a unique characteristic of Y-TZP, as it undergoes a phase transformation process resulting in local volume expansion, which counteracts crack propagation (Piconi & Maccauro, 1999; Denry & Kelly, 2008; Hisbergues et al., 2009). Preclinical investigations have shown that zirconia can withstand masticatory forces over an extended period of time (Akagwa et al., 1993; Akagwa et al., 1998; Silva et al., 2009; Kohal et al., 2010). Animal experiments evaluating the biocompatibility and osseointegration of zirconia ceramics revealed favourable results comparable to standard titanium implants (Sennerby et al., 2005; Deprrich et al., 2008; Hoffmann et al., 2008). There is now a need for well-designed clinical trials to evaluate the clinical performance of these systems before recommending the routine use of zirconia implants in daily practice.

The outcome of zirconia implants has been recently reviewed, based on the available clinical data from case reports, prospective, retrospective and randomized multicenter studies (Deprrich et al., 2012). The reported survival rates ranged from 74 to 98% after observation periods of 12 to 56 months. The authors advised caution in interpreting these results, due to the short observation periods, small numbers of participants, the minimal information
provided on study methods and the low level of evidence extracted from these studies. Similarly, a number of systematic reviews have commented on the scarcity of clinical data supporting the use of zirconia implants (Wenz et al. 2008; Andreiotelli et al. 2009), mainly limited to cohort investigations of lower evidential value (Wenz et al., 2008; Andreiotelli et al., 2009).

In the majority of these studies zirconia implants were used for single tooth replacements, mainly in the anterior, premolar regions and to a lesser extent in the molar region (Borgonovo et al., 2010; Cannizzaro et al., 2010; Payer et al., 2012). There is increasing concern expressed by patients regarding the potential health hazards of titanium and its corrosive products, leading to requests for metal-free protocols in the treatment of edentulous patients (Kohal et al., 2012). We have identified a lack of published literature on the use of zirconia implants to support overdentures. The aim of this randomized controlled trial was to evaluate the hypothesis that for maxillary and mandibular implant overdentures, there would be no difference in either clinical success (survival/failure) or marginal bone levels among two groups of participants receiving either one-piece zirconia or titanium implants of the same design, in the context of a novel protocol for implant distribution.

**MATERIALS AND METHODS**

The consort guidelines for improving the quality of randomized trials (Altman et al., 2001; Moher et al., 2003) were followed in this trial. The study protocol was approved by the Regional Lower South Ethics Committee of New Zealand (LRS/09/06/023), and all participants gave signed informed consents.

**Participant selection and study Design**

Participants were selected from a pool of patients referred to, or reporting to, the Faculty of Dentistry, University of Otago, with functional problems in the use of their complete dentures. Strict inclusion criteria for the participants were: maladaptive conventional denture experience, recurrent problems with existing complete dentures including soft tissue lesions or infections, and adequate bone volume to accommodate the implants (length: 10–13.5 mm; diameter: 3.8–5.0mm). Exclusion criteria included any medical conditions contraindicating implant surgery, irradiated or bone-grafted jaws, use of intravenous bisphosphonates, heavy smoking (more than 10 cigarettes per day), and any known metal allergies.
Sequence of treatment

Pre-treatment examination

There were 24 participants in this trial. Orthopantomography and spiral tomography were taken for the first two participants; the remainder were examined using cone-beam computed tomography (Sirona, Galileos, Bensheim, Germany). The length and the diameter of the implants were chosen according to the reconstructed 3D images of the maxillary and mandibular arches.

Each participant was supplied with diagnostic complete maxillary and mandibular dentures, fabricated according to a standardized prosthodontic protocol (Zarb et al., 2013). Participants wore their complete dentures for approximately eight weeks to allow adaptation. A simple randomization method was performed in accordance with items 8-10 of the CONSORT statement 2001-checklist for the randomized controlled clinical trials (Cochrane Collaboration, Manchester, UK). The principal investigator blindly allocated 24 participants to either of the two groups (zirconia or titanium) by asking them to pick one of a sequentially numbered set of opaque sealed envelopes containing either of the two interventions. By this way each participant had an equal chance of being assigned to one of the two groups. Blinding of the outcome assessors to the interventions was not possible in this study.

Implant design and characteristics

Identical one-piece ceramic and titanium implants were manufactured by Southern Implants (Irene, South Africa). These comprised of a tapered threaded implant body, a trans-mucosal cylindrical collar and a ball abutment, all in a single component (Fig 4.1). The zirconia implants consisted of 95% zirconia with yttria and alumina making up the remaining 5%. The surface of the ceramic implants was roughened using concentrated solution of nitric and hydrofluoric acid-etching technique resulting in a mean surface roughness $R_a$ value of 0.73 µm. The titanium implants were both acid-etched and sandblasted with a mean surface $R_a$ value of 1.43 µm. The lengths of the implants provided were 11.5, 10, 8 and 6 mm, in a regular 3.8 mm and a wider 5mm platform diameter. Diameters of ball abutments available were 3.1mm and 2.25mm.
Surgical procedures

For each participant the maxillary and mandibular surgeries were performed at separate appointments. All the surgical procedures were carried out by the same surgeon. Before the surgeries the patients were pre-medicated with 2 g amoxicillin and 1 g paracetamol. Local anesthesia was administered for the implant placement; quadrilateral and tripodal design for the maxilla and mandible respectively. All the implants except the mid-palatal implant were placed according to a flap protocol; standard drilling with low speed and thorough irrigation to prevent bone overheating. For the palatal implant no flap was raised rather a trephine was used to remove a punch of palatal mucosa corresponding to the selected implant diameter. The center of the exposed cortical plate was then indented with a small round bur to help locate the profile drill. Then drilling was carried out according to the selected implant length. A conventional 12 week healing period was followed before the pick-up of attachments.

Implant sites

Each participant received four implants in the maxilla and three implants in the mandible (Fig 4.2). In the maxilla, implant distribution was as follows: (a) off-center implant in the incisal region (b) bilateral implants in the premolar regions (c) a mid-palatal implant, posterior to the two distal implants, resulting in a diamond-shape distribution (Osman et al.,
2013 a). In the mandible, one implant was placed in the mid-line of the mandibular symphysis and bilateral implants were placed in the first molar regions (Osman et al., 2013 a).

**Prosthodontic procedures**

Following implant surgery, the intaglio surfaces of complete dentures were relieved and relined with a tissue conditioning material (Visco-gel, Dentsply). Following a conventional loading protocol, closed-mouth impressions were made at a 12 week healing period with polyether material (Impregum™ Penta™, 3M ESPE) to incorporate the respective matrices into the intaglio surface of the overdentures. An unsplinted prosthodontic design was used for all participants in both groups. The attachment systems comprised ball abutments (patrices) as part of the one-piece titanium or zirconia implants of different diameters (Fig 4.2). All maxillary implants had 2.25-mm patrices, while mandibular implants had either 2.25-mm or 3.1-mm patrices. The patrices were made of unalloyed grade 4 titanium with titanium nitride coating of 2.0 – 3.0 μm thickness or yttrium-stabilized tetragonal polycrystalline zirconia (Y-TZP). The corresponding plastic resin matrices were made from polyoxymethylene copolymer.

Laboratory procedures were standardized with two experienced dental technicians using semi-adjustable articulators (Artex®, AmannGirrbach, Germany), acrylic denture teeth (Vita Physiodens for anterior and Vita Lingoform for posterior teeth), heat-cure denture base acrylic resin (WHW Universal Acrylic Denture Base, WHW Plastics, UK) and lingualized occlusion. No reinforcement of the dentures was done with any metal alloy framework. Delivery procedures of all implant overdentures were standardized (Payne & Zarb, 2013).
Figure 4.2 Clinical photos of control and test groups rehabilitated with implant overdentures supported by one-piece (a, c) titanium and (b, d) zirconia implants with (e, f) respective attachment systems

Outcome measures

Implant success

Implant success was evaluated using the four-field table defined by Albrektsson & Zarb (1993) and Ross et al. (1997) with the following categories success, survival, unaccounted for and failure. An implant meeting the success criteria should exhibit less than 1mm bone loss during the first year and should be free of mobility, pain and neuropathy. Implants that were still functioning but did not meet the success criteria were considered as surviving. Implants in patients who dropped out of the study for any reason were considered as unaccounted for.
An implant removed for any reason was considered as a failure. Radiographs were not taken of the mid-palatal implants, these were rated as successful if clinically stable without any mobility and classified as failures if mobile.

Peri-implant marginal bone levels

Standardized radiographs were taken at the time of loading (pick-up of attachments) and after one year, using a long-cone parallel technique with customized radiographic stents (Payne et al., 1999). Radiographs were scanned, digitized as JPG files, converted to a TIFF format with 600 dpi resolution, and stored in a personal computer. Peri-implant marginal bone levels were measured using image analysis software (Image J 1.34S, National Institutes of Health, USA). The software was calibrated for each image using the known distance of the implant collar (1.5 mm). The reference points for mesial and distal bone crest measurements were the top of the ball abutment and the most coronal point of bone-to-implant contact (Fig. 4.3). Measurements of mesial and distal surfaces for each group were averaged and compared statistically. To evaluate the inter-observer reliability, a second observer repeated the measurements independently in fifteen radiographs maintaining the same conditions.

Figure 4.3 Radiographic marginal bone level measurements made from a predefined reference point (red line) to the first implant to bone contact (yellow arrow) at either side of each implant.

Prosthodontic outcomes

The prosthodontics outcomes will be presented in part II of this Chapter.
Statistical analysis

Statistical software (SPSS 17.0, SPSS Inc., Chicago, IL, USA) was used in the analysis of the data. Histogram, stem and leaf plot, box plot, measures of skewness and kurtosis as well as Shapiro-Wilk and Kolmogorov-Smirnov tests, were used to assess the normality of quantitative data. Radiographic bone level change was the main response variable used in the study to evaluate the clinical performance of the two implant materials. Difference in mean marginal bone level (MBL) changes between the two groups was tested using Independent Samples t-tests, with the implant as the statistical unit. The Chi-square was used to compare the categorical variables such as implant survival, among the different groups. Implant survival was presented in two modes, by edentulous arch (mandible vs. maxilla) and by implant material (titanium vs. zirconia). The significance for statistical analysis was set at \( P < 0.05 \).

A binary logistic model was used to predict the risk indicators for implant failure. The model is used for categorical dichotomous outcome (Implant survival was coded 0 while implant failure was coded 1). Variables which had \( P \)-values of less than 0.05 were considered as significant predictors in this model.

RESULTS

Patient demographics

The mean age of the participants was 62 years (range 46 to 80 years) and two-thirds were males (15 men and four women). Of the original 24 participants recruited, only 19 were available at the one-year follow-up. This represents a total of 129 implants available for analysis (56 titanium and 73 zirconia implants). Five participants and 35 implants were not available for follow-up after one year. Of this five, two participants in the titanium group dropped out due to relocation and were lost to follow-up. Three participants died, two from the titanium group and one from the zirconia group, accounting for 21 of the implants lost to follow-up after one year. According to their relatives, all the implants in these individuals were still in function at the time of death.

Each participant except two received seven implants (four in the maxilla and three in the mandible). Two participants received one or three implants respectively in the maxilla – this was dictated by the amount of bone available at the time of surgery. A further three
participants (one in the titanium group and two in the zirconia group) had early maxillary implant failures and were converted to conventional complete dentures.

Out of the 129 implants placed, 56% (32 titanium and 40 zirconia implants) were placed in the maxilla and 44% (24 titanium and 33 zirconia) in the mandible. Seventy-one implants (55%) were wide-platform implants with a diameter of 5mm and lengths varying from 6 to 11.5mm, whilst 58 implants had a regular diameter of 3.8 mm and were of either 10 or 11.5 mm length. Specification of implant length and diameter with respect to intra-oral position is given in Table 4.1.

<table>
<thead>
<tr>
<th>Distribution (Site) of implants</th>
<th>No. of Implants</th>
<th>Implant Diameter and Length</th>
<th>% of Implants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior maxilla</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Region 14</td>
<td>18</td>
<td>ø3.8x10mm (10)</td>
<td>14%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ø3.8x11.5mm (8)</td>
<td></td>
</tr>
<tr>
<td>Off center</td>
<td>17</td>
<td>ø3.8x10mm (10)</td>
<td>13.2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ø3.8x11.5mm (7)</td>
<td></td>
</tr>
<tr>
<td>Region 24</td>
<td>18</td>
<td>ø3.8x10mm (10)</td>
<td>14%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ø3.8x11.5mm (8)</td>
<td></td>
</tr>
<tr>
<td>Mid-Palatal</td>
<td>19</td>
<td>ø5 x6mm (19)</td>
<td>14.7%</td>
</tr>
<tr>
<td>Mid-symphysis</td>
<td>19</td>
<td>ø3.8x10mm (3)</td>
<td>14.7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ø3.8x11.5mm (2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ø5 x10mm (4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ø5 x11.5mm (10)</td>
<td></td>
</tr>
<tr>
<td>Posterior mandible</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Region 36</td>
<td>19</td>
<td>ø5 x6mm (3)</td>
<td>14.7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ø5 x8mm (8)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ø5 x10mm (7)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ø5 x11.5mm (1)</td>
<td></td>
</tr>
<tr>
<td>Region 46</td>
<td>19</td>
<td>ø5 x6mm (2)</td>
<td>14.7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ø5 x8mm (9)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ø5 x10mm (7)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ø5 x11.5mm (1)</td>
<td></td>
</tr>
</tbody>
</table>
Implant outcomes

From the time of implant placement to prosthesis insertion, 14 implants failed. From prosthesis insertion to one-year follow-up, another 14 implants failed. This included 10 implants in the titanium group and 18 implants in the zirconia group (Table 4.2). Details of implant failures according to the location and time point of failures are shown in Table 4.3. Three implants in the zirconia group fractured - one in the mandible and two in the maxilla. Further, three implants successfully osseointegrated but could not be used due to their deep placement. These three implants were classified as “surviving”, resulting in an overall combined survival rate for all implants in this trial of 75.9%. There was no significant difference in the survival rate between the two implant groups in either jaw (Tables 4.4 and 4.5). In the mandible, titanium implants showed a survival rate of 95.8% versus 90.9% for the zirconia implants ($P=0.47$). The corresponding values in the maxilla were 71.9% and 55% for the titanium and zirconia groups respectively ($P=0.14$) (Tables 4.6 and 4.7). No statistically significant difference was found in the survival rate between anterior and posterior implants in the mandible or between crestal and mid-palatal implants in the maxilla (Tables 4.8 and 4.9). All failed implants were replaced three to four months after removal and were successful in most of cases. These implants were not included in the study.

The Prediction model for implant failure using binary logistic regression revealed that the implants placed in the maxilla were at the highest risk of failure ($P<0.0001$) (Table 4.10).

| Table 4.2 Overall outcome of all the implants available at the 1-year follow-up |
|----------------------------------------|-----------------|-----------------|---|
| **Titanium implant group (n = 56)**    | 10 (17.9%)      | 46 (82.1%)      | 0.15* |
| **Zirconia implant group (n = 73)**    | 21 (28.8%)      | 52 (71.2%)      |     |

*No statistically significant difference between groups ($P>0.05$)
Table 4.3 Distribution of failure according to implant location

<table>
<thead>
<tr>
<th>Location</th>
<th>No of implants placed</th>
<th>No of failures</th>
<th>Time point of</th>
<th>Location</th>
<th>No of implants placed</th>
<th>No of failures</th>
<th>Time point of</th>
</tr>
</thead>
<tbody>
<tr>
<td>No of failures (%)</td>
<td></td>
<td></td>
<td></td>
<td>No of failures (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mx. Ant Crestal</td>
<td></td>
<td></td>
<td></td>
<td>Titanium</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zirconia</td>
<td>29</td>
<td>13 (44.8)</td>
<td>10 Early failures</td>
<td>3 Late failures</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Titanium</td>
<td>24</td>
<td>6 (25)</td>
<td>5 Late failures</td>
<td>1 Early failures</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mid-palatal</td>
<td></td>
<td></td>
<td></td>
<td>Mid-palatal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zirconia</td>
<td>11</td>
<td>5 (45.4)</td>
<td>Early failures</td>
<td>Titanium</td>
<td>8</td>
<td>3 (37.5)</td>
<td>Late failures</td>
</tr>
<tr>
<td>Mid-Symph</td>
<td></td>
<td></td>
<td></td>
<td>Mid-Symph</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zirconia</td>
<td>11</td>
<td>1 (9)</td>
<td>Late failure (fracture)</td>
<td>Titanium</td>
<td>8</td>
<td>1(12.5)</td>
<td>Early failure</td>
</tr>
<tr>
<td>Post. Mand</td>
<td></td>
<td></td>
<td></td>
<td>Post. Mand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zirconia</td>
<td>22</td>
<td>2 (9)</td>
<td>Late failures</td>
<td>Titanium</td>
<td>16</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zirconia</td>
<td>73</td>
<td>21 (28.7)</td>
<td></td>
<td>Titanium</td>
<td>56</td>
<td>10 (17.8)</td>
<td></td>
</tr>
</tbody>
</table>

Mx. Ant Crestal: Maxillary anterior crestal implants
Mid-Symph: Mid-symphysis
Post. Mand: Posterior mandibular
Early failure: before pick-up of attachments
Late failure: after pick-up of attachments

Table 4.4 Outcome of implants in the mandible by the implant material

<table>
<thead>
<tr>
<th>Implant Material</th>
<th>Failure N (%)</th>
<th>Survival N (%)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium implant group (n = 24)</td>
<td>1 (4.2%)</td>
<td>23 (95.8%)</td>
<td>0.47*</td>
</tr>
<tr>
<td>Zirconia implant group (n = 33)</td>
<td>3 (9.1%)</td>
<td>30 (90.9%)</td>
<td></td>
</tr>
</tbody>
</table>

* No statistically significant difference between groups (P>0.05)
Table 4.5 Outcome of implants in the maxilla by the implant material

<table>
<thead>
<tr>
<th>Group</th>
<th>Failure N (%)</th>
<th>Survival N (%)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium implant group (n = 32)</td>
<td>9 (28.1%)</td>
<td>23 (71.9%)</td>
<td>0.14*</td>
</tr>
<tr>
<td>Zirconia implant group (n = 40)</td>
<td>18 (45.0%)</td>
<td>22 (55.0%)</td>
<td></td>
</tr>
</tbody>
</table>

* No statistically significant difference between groups (P>0.05)

Table 4.6 Outcome of titanium implants (Survival/Failure) per each edentulous arch

<table>
<thead>
<tr>
<th>Group</th>
<th>Failure N (%)</th>
<th>Survival N (%)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maxillary implant group (n = 32)</td>
<td>9 (28.1%)</td>
<td>23 (71.9%)</td>
<td>0.021*</td>
</tr>
<tr>
<td>Mandibular implant group (n = 24)</td>
<td>1 (4.2%)</td>
<td>23 (95.8%)</td>
<td></td>
</tr>
</tbody>
</table>

* Statistically significant difference between groups (P<0.05)

Table 4.7 Outcome of zirconia implants (Survival/Failure) per each edentulous arch

<table>
<thead>
<tr>
<th>Group</th>
<th>Failure N (%)</th>
<th>Survival N (%)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maxillary implant group (n = 40)</td>
<td>18 (45.0%)</td>
<td>22 (55.0%)</td>
<td>0.001*</td>
</tr>
<tr>
<td>Mandibular implant group (n = 33)</td>
<td>3 (9.1%)</td>
<td>30 (90.9%)</td>
<td></td>
</tr>
</tbody>
</table>

* Statistically significant difference between groups (P<0.05)

Table 4.8 Implant Outcome per site in mandible (Anterior vs. Posterior)

<table>
<thead>
<tr>
<th>Group</th>
<th>Failure N (%)</th>
<th>Survival N (%)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior (long) implant group (n = 19)</td>
<td>2 (10.5%)</td>
<td>17 (89.5%)</td>
<td>0.46*</td>
</tr>
<tr>
<td>Posterior (short) implant group (n = 38)</td>
<td>2 (5.3%)</td>
<td>36 (94.7%)</td>
<td></td>
</tr>
</tbody>
</table>

* No statistically significant difference between groups (P>0.05)

Table 4.9 Implant Outcome per site in maxilla (Anterior crestal vs. Mid-Palatal)

<table>
<thead>
<tr>
<th>Group</th>
<th>Failure N (%)</th>
<th>Survival N (%)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crestal implant group (n = 53)</td>
<td>19 (35.8%)</td>
<td>34 (64.2%)</td>
<td>0.63*</td>
</tr>
<tr>
<td>Mid-palatal implant group (n = 19)</td>
<td>8 (42.1%)</td>
<td>11 (57.9%)</td>
<td></td>
</tr>
</tbody>
</table>

* No statistically significant difference between groups (P>0.05)
Table 4.10 Prediction model for implant failure

<table>
<thead>
<tr>
<th>Predictor variable</th>
<th>Outcome: implant failure</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B coefficient (SE)</td>
<td>P-value</td>
<td>Odds ratio (95% CI)</td>
</tr>
<tr>
<td>Age (&lt;65)</td>
<td>-0.46 (0.48)</td>
<td>0.34</td>
<td>0.63</td>
</tr>
<tr>
<td>Implant material</td>
<td>-0.33 (0.48)</td>
<td>0.33</td>
<td>0.63</td>
</tr>
<tr>
<td>Edentulous arch</td>
<td>2.41 (0.66)</td>
<td>&lt; 0.0001*</td>
<td>11.1</td>
</tr>
<tr>
<td>Implant length</td>
<td>0.55 (0.50)</td>
<td>0.28</td>
<td>1.7</td>
</tr>
<tr>
<td>Constant</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model Chi-square = 23.9; df = 5; P &lt; 0.0001*</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Statistically significant difference between groups (P<0.05)

Marginal bone remodeling

From prosthesis insertion to the one-year follow-up, a mean radiographic bone loss of 0.2mm was observed. Of the 86 implants which were evaluated radiographically, 16 (18.6%) implants demonstrated a gain in crestal bone height. None of the implants showed more than 1mm bone loss at the end of the one-year observation period. For both jaws combined, less mean marginal bone loss was observed around titanium implants (0.18mm, SD 0.47) compared to the zirconia group (0.42mm, SD 0.40) (Table 4.11) and this difference was statistically significant between the two groups (P<0.05). No significant difference was found in the marginal bone level between the two implant materials in the maxilla (P= 0.21) (Table 4.12). Conversely, significantly more bone loss occurred around zirconia implants in the mandible (P= 0.024) (Table 4.13). The one-year implant outcomes are illustrated using a four-field table analysis as proposed by Albrektsson & Zarb (1993) (Table 4.14).

Table 4.11: Mean and standard deviation of marginal bone change by implant material

<table>
<thead>
<tr>
<th>Treatment group</th>
<th>No. of implants</th>
<th>Mean (SD)</th>
<th>Mean difference &amp; 95% CI</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium group (control)</td>
<td>40</td>
<td>0.18 (0.47)</td>
<td>-0.25 (-0.44,-0.66)</td>
<td>0.009*</td>
</tr>
<tr>
<td>Zirconia group</td>
<td>46</td>
<td>0.42 (0.40)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Statistically significant difference between groups (P<0.05)
Table 4.12: Mean and standard deviation of marginal bone change by implant material in maxilla

<table>
<thead>
<tr>
<th></th>
<th>Titanium implant group (n = 18) Mean (SD)</th>
<th>Zirconia implant group (n = 16) Mean (SD)</th>
<th>Mean difference and 95% CI</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marginal bone changes</td>
<td>0.21 (0.48)</td>
<td>0.38 (0.27)</td>
<td>-0.17 (-0.44, 0.10)</td>
<td>0.2&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup> No statistically significant difference between groups (P>0.05)

Table 4.13: Mean and standard deviation of marginal bone change by implant material in mandible

<table>
<thead>
<tr>
<th></th>
<th>Titanium implant group (n = 22) Mean (SD)</th>
<th>Zirconia implant group (n = 30) Mean (SD)</th>
<th>Mean difference and 95% CI</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marginal bone changes</td>
<td>0.15 (0.47)</td>
<td>0.45 (0.45)</td>
<td>-0.30 (-0.56, -0.42)</td>
<td>0.024&lt;sup&gt;*&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Statistically significant difference between groups (P<0.05)

Table 4.14: Implant Outcome: Four-Field table analysis (Albrektsson & Zarb 1993)

<table>
<thead>
<tr>
<th>Treatment group</th>
<th>Success&lt;sup&gt;a&lt;/sup&gt; No. (%)</th>
<th>Survival&lt;sup&gt;b&lt;/sup&gt; No. (%)</th>
<th>Unaccounted for&lt;sup&gt;c&lt;/sup&gt; No. (%)</th>
<th>Failure&lt;sup&gt;d&lt;/sup&gt; No. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium group (control)</td>
<td>40 (57.1)</td>
<td>6 (8.5)</td>
<td>14 (20)</td>
<td>10 (14.2)</td>
</tr>
<tr>
<td>Zirconia group</td>
<td>46 (57.5)</td>
<td>6 (7.5)</td>
<td>7 (8.7)</td>
<td>21 (26.2)</td>
</tr>
</tbody>
</table>

<sup>a</sup> Implants with less than 1mm bone loss during the first year and free of pain, mobility and neuropathy
<sup>b</sup> Included all surviving mid-palatal implants and osseointegrated deeply placed implants that could not be used.
<sup>c</sup> Included all the implant that could not be followed due to patients drop out for any reason.
<sup>d</sup> All the implants removed for whatever reason.

**DISCUSSION**

This randomized controlled trial evaluated the clinical success (survival/failure rate) and marginal bone levels of one-piece zirconia (Y-TZP) implants, compared with titanium implants of the same design, when used for the support of maxillary and mandibular overdentures.

The protocol for distribution of the implants had a number of novel aspects, with two implants in the molar region of the mandible forming a tripod support with a midline implant,
and four implants in the maxilla including a mid-palatal implant. It is acknowledged that with this new approach, it was difficult to compare the outcomes to those of robust long-term evidence on overdentures using two-piece titanium implants. The strength of the study was reduced due to the small patient cohort, unequal group size and short observation period of one year, although new interventions in human clinical trials often necessitate small sample sizes in order to justify larger-scale interventions (Attard & Zarb, 2004; Alsabeeha et al., 2011). However, the standardization of multiple variables (implant design, surface characteristics, implant distribution, prosthodontic /laboratory procedures and status of the opposing arch) was pertinent. A priori sample size calculation was not attempted but it is believed that the sample size was sufficient to detect a statistically significant difference in the marginal bone levels between the two groups.

\textit{In-vitro} and \textit{in-vivo} studies have shown that zirconia implants are highly biocompatible and capable of withstanding masticatory forces under different loading conditions. The clinical use of zirconia implants for rehabilitation of partially edentulous patients is well established, with promising results albeit in the short term. However, similar data on the use of zirconia implants for support and retention of overdentures is lacking. Our study is the first clinical trial to evaluate the outcomes of zirconia oral implants for overdenture support. This novel approach if proven to be valid will help address the increasing concerns regarding the potential health hazards of titanium particles and corrosive products and satisfy the needs of edentulous patients requesting metal-free restorations (Kohal et al., 2012).

Acknowledging the brittle nature of zirconia implants, we decided to adopt a novel implant distribution, to optimize load distribution and improve the peri-implant biomechanical environment. Detailed description of the design rationale has been described elsewhere (Osman et al., 2013 a). A conventional loading protocol was followed in this study. The dentures were either not worn for one to two weeks after surgery, or were completely relieved from the ball abutments. Three to four months later the definitive prostheses with attachments were connected. Since our study employed single-piece implants placed using a one-stage surgical approach, the possibility that indirect loading of the implants occurred prior to fitting the definitive prosthesis cannot be discounted (Tawse-Smith et al., 2001; Prithviraj et al., 2012). We did not include a control group where the implants were placed and allowed to heal for four months without any prosthesis being worn, and thus the effect of immediate function on the clinical outcomes could not be evaluated.
The overall survival rate of 71.2% for zirconia implants in the current study is far below the figures reported in other clinical trials using one-piece zirconia implants. In a retrospective study, Mellinghoff (2006) reported 93% one-year survival rate for 189 zirconia implants (Y-TZP) inserted in 71 patients. In their study, only 53 implants had received a definite prosthetic construction (crowns or fixed partial dentures) at the time of the last recall visit. In a further retrospective study comparing rough-surfaced titanium implants and one-piece zirconia implants, a survival rate of 84.4% and 98.4% was found for zirconia implants in the maxilla and mandible respectively (Lambrich & Ighaut, 2008). Oliva et al. (2007) presented the results after one year for 100 one-piece zirconia dental implants with two different surfaces inserted into 36 patients. The overall implant success rate was 98% in both the bioactive ceramic coated and non-coated groups. Two prospective studies reported an overall success rate of 92 to 95% for one-piece zirconia implants over a follow-up period ranging from 2.5 to 5 years (Pirker & Kocher, 2009; Oliva et al., 2010a). However, in those two studies there was no mention of marginal bone levels and the reported success rate was actually a description of implant survival.

The difference in outcome between these studies and our study may be due to the prosthodontics reconstruction. In most of the above studies, zirconia implants were used for single tooth replacement in the anterior or premolar region, where less occlusal load would be anticipated. Thus it may be speculated that zirconia implants perform more favorably when used for rehabilitation of partially edentulous cases, particularly in anterior esthetic regions, rather than when used for overdenture support. Nevertheless, the results of these studies should still be regarded cautiously as the study designs include a limited number of patients and implants and short observation periods.

Gahlert et al. (2012b) reported the failure rate of zirconia implants, based only on the incidence of fracture after prosthodontic restoration, as being 10%, where 13 out of 170 inserted implants fractured after 20 to 50 months in function. In our study, three implants fractured in the zirconia group by the end of the one-year follow-up period, resulting in a fracture failure rate of 4.1%. Unfavorable bending moments associated with corono-apical bone resorption and loss of supporting bone has been suggested as the most probable causes for implant fracture (Rangert et al., 1995). Further contributing factors might be small implant diameter (φ 3.75 mm) and identical design of the zirconia implants to those of the titanium with insufficient attention to design optimization for ceramic implants (Tagger Green et al., 2002). In two participants in our study, the maxillary implant fractured following the failure
and loss of the mid-palatal and anterior crestal implant. As the maxillary overdenture was then supported by two implants in the premolar region bilaterally, we suggest that the straight-line geometry of the two remaining implants may have resulted in greater bending moments on the remaining implants. Therefore, it is the recommendation of this study that a minimum number of four implants be used when zirconia implants are employed for maxillary overdenture support combined with the selection of wider diameter implant as dictated by anatomical situation. The only incidence of mid-symphysisal implant fracture was due to limited dexterity of the patient and his inability to manipulate the dentures without applying undue bending forces on implants. Thus, the importance of evaluating the patients’ dexterity particularly when zirconia implants are employed for overdentures support cannot be overemphasized. Higher fracture incidence encountered in the zirconia group calls for further modifications of implant design to improve its biomechanical integrity.

After one year of function, peri-implant marginal bone levels differed significantly between titanium and zirconia implants (P< 0.05). We suggest that the difference in surface roughness between the two implant materials may partly account for this. In our study, the zirconia implants had a minimal surface roughness (Rₐ 0.73 µm) and the titanium implants had a moderately rough surface (Rₐ 1-2µm). In their review Albrektsson and Wennerberg (2004a & b) concluded that moderately roughened titanium surfaces are clinically advantageous compared with smoother surfaces, and we suggest that surface microtopography is also an important factor for the osseointegration of zirconia implants (Wenz et al., 2008; Wennerberg & Albrektsson, 2009). This is supported by experimental research in animal models. In a minipig model Depprich et al. (2008) found a slightly higher, though not statistically significant, bone implant contact on titanium implants compared to zirconia. Both types of implants used had the same macroscopic design, with modified acid etched surface. Ra values were reported to be 0.598 µm and 1.8 µm for zirconia and titanium implants respectively. A similar finding was also reported by another group in a different animal model (Hoffmann et al., 2008). However, the latter study did not state the surface roughness of the different implants, the sample size was small and the authors recommended the results to be regarded as preliminary. Others have reported a weaker bone response and lower torque removal values when minimally-rough zirconia implants were compared to moderately rough surfaced zirconia implants in different animal models (Kohal et al., 2004; Sannerby et al., 2005; Gahlert et al., 2007; 2009). We feel that further biomaterial science research is needed with the aim of producing similar surface characteristics on zirconia
implants to those already established as the optimum for osseointegration of titanium implants.

Another possible explanation for the increased bone loss around zirconia implants could be the difference in modulus of elasticity between the two implant materials. According to VonRecum (1986), when two materials with a different modulus of elasticity are placed together without an intervening material and one is loaded, a stress concentration zone is observed where the two materials first contact. The rigidity of zirconia (220 GPa) is almost double that of titanium (104 GPa) which may result in an increased stress concentration in peri-implant bone. This did not affect survival rates, which were comparable between the two groups, but may have modified the response of peri-implant crestal bone. A recent finite element analysis comparing the stress/strain distribution between zirconia and titanium implants supporting maxillary overdentures, revealed strain values of 2823 µε and 2497 µε for zirconia and titanium implants respectively (Osman et al., In Press-a). According to Wolf’s Mechanostat theory, both values were within the physiological remodeling range of the bone (Frost, 2001).

The significant difference in marginal bone level between zirconia and the titanium implants in the mandible but not in the maxilla may be related to differences in bone quantity and quality in the mandible compared to the maxilla (Bryant 1999). A review of the literature on the influence of age, jaw site and bone conditions on oral implants outcome concluded that the osseointegration potential does appear to be site-specific, as demonstrated by somewhat higher success rates reported for implants in the anterior mandible compared to the maxilla (Bryant, 1999). In the same context, Schwartz-Arad et al. (2005) found that the implant location was the most influential factor affecting crestal bone loss around implants supporting maxillary and mandibular overdentures. In our study, the low success rate observed for both titanium (57.1%) and zirconia (57.5%) implants was largely related to implant failures in the maxilla. Furthermore, we recorded the outcome of mid-palatal implants in the survival category since we could not acquire radiographic images of these implants; this also reduced the percent success rate.

We found a mean bone loss of 0.41 mm between base line and 1-year in the zirconia group, which is comparable to results from other studies. Cannizzaro et al. (2010) found an average of 0.7 mm and 0.9 mm bone loss after one year loading, for immediately non-occlusal loaded and occlusally loaded single-piece zirconia implants, respectively. The implants were
used for single tooth replacements and had sand-blasted surfaces although the surface roughness \( (R_a) \) values were not specified. In another prospective case series, bone loss of 1.01 mm was reported for 20 zirconia implants with a surface roughness of \( S_a 1.17 \) \( \mu \)m inserted in single tooth gaps in the maxilla \( (N=11) \) and mandible \( (N=9) \) of 20 patients (Payer et al., 2012). Although the findings of these two studies may not directly apply to the treatment approach used in our study, their clinical findings also support the use of zirconia implants.

Our trial compared implants fabricated from zirconia to those made of titanium, both having a single-piece design. Conflicting results have been presented in the literature on the outcome of single-piece titanium implants. Several authors reported a high failure rate and extensive marginal bone loss of more than 2 mm around Nobel Direct\textsuperscript{®} and Nobel Perfect\textsuperscript{®} single-piece titanium implants after an average follow-up of one year (Nowzari et al., 2006; Albrektsson et al., 2007; Östman et al., 2007; Sennerby et al., 2008; Van de Velde et al., 2009), whereas others reported stable marginal bone levels and soft tissue health (Finne et al., 2007; Hahn, 2007; Siepenkothen, 2007). The single-piece titanium implants in our study achieved a stable marginal bone level with an average bone loss of 0.1 mm after one-year follow-up. Implicated in the high failure rate were three factors: implant design (one-piece design, moderately-rough surface in contact with mucosa), surgical protocol (flapless placement) and prosthodontic protocol (immediate loading) (Albrektsson et al., 2007; Östman et al., 2007). The titanium implants that we used had a rough surface in contact with bone but presented a smooth surface to mucosa, and flapless surgery was only used for the palatal implants. Survival rates for our one-piece immediately-loaded titanium implants in the mandible were acceptable, but these results were poor in the maxilla. We suggest that the reason for this may rest with the anatomical location and bone quality, rather than the three factors suggested for Nobel one-piece titanium implants.

In agreement with previous studies, we found higher failure rates for both titanium and zirconia implants in the maxilla compared to the mandible \( (P<0.05) \) (Drago, 1992; Johns et al., 1992; Cune & de Putter, 1996; Chan et al., 1998; Esposito et al., 1998a; Moy et al., 2005). Similarly, the prediction model for implant failures revealed a higher risk for implants placed in the maxilla. This may partly be explained by the difference in bone quality between the two edentulous arches (Bryant, 1998; Esposito et al., 1998b). Generally, the mandible has a denser and thicker cortical layer than maxilla. Also the trabecular bone component is denser in mandible than in the maxilla (Bryant, 1998; Esposito et al., 1998b). The presence of dense
bone in the mandible may favor early implant stabilization, which is one of the prerequisites for predictable osseointegration (Truhlar et al., 1997). Furthermore, differences in healing patterns between cortical and trabecular bone may be of importance (Bryant, 1998). Wider diameter implants in combination with prolonged healing have been recommended when limited cortical bone is present (Lekholm, 1998). The reason for the latter is that cancellous bone needs a longer period to reach the same load-bearing capacity as cortical bone (Sennerby et al., 1992; Bryant, 1998). Unfortunately the pattern of bone resorption in fully-edentulous maxillae often precludes the use of wide-body implants (Chan et al., 1998).

Accurate diagnosis and treatment planning is of the utmost importance for optimizing treatment outcome. This should include the use of implant systems with well-established surface characteristics, selection of optimal implant recipient site with adequate bone quantity and quality and the use of conventional loading protocol to enhance the process of osseointegration.

We employed a modified protocol for mandibular implant distribution, a combination of single implants placed into bilateral molar sites (distal to the mental foramina) with a single midline implant. There are few reports of this in the literature. It has been suggested that that bone in zone II (posterior to the mental foramina) in both arches often presents with poorer bone quality (type 3 or 4) than that observed in zone 1 (Lekholm & Zarb, 1985). However, it has been argued that this may not apply in the mandible. Zone I of the mandible usually has a moderate to high trabecular density and cortical thickness, and rarely presents with an insufficient height or width for implant placement. Nevertheless, it was also reported that although the posterior mandible presents most commonly with a low trabecular density, it typically has an increased thickness of buccal cortex compared with the anterior mandible. Histomorphometric examination of edentulous jaws has shown that the external layer of cortical bone is significantly wider in the mandible than in the maxilla and is twice as wide in the anterior as in the posterior segments of the mandible (Lindhe et al., 2013). Conceptually, then, a typical posterior mandible might be described as having either type 2 bone with low trabecular density, or type 4 bone with a thick cortex; neither of which fits the Lekholm and Zarb classification accurately. This highlights the need for a more detailed and robust bone classification systems that better describes different clinical situations.

The use of implants with the longest feasible length has been advocated based on the axiom that longer implants would guarantee better survival rates and more favorable
prognosis (Lee et al., 2005). According to the recent literature, a short implant is defined as an implant with an intra-bony length of 8mm or less (Neldam & Pinholt, 2012). The use of short implants has been considered biomechanically disadvantageous, particularly when combined with poor bone quality and high occlusal loads. However, with the development of implant design, surface structure, and improved surgical technique, it may be time to re-evaluate this concept. Recent literature has reported high predictability and favorable survival rates of 96% to 100% for short implants and has supported their use in situations of reduced alveolar heights in the posterior jaw (Griffin & Cheung, 2004; Misch et al., 2006; Malô et al., 2007; Fugazzotto, 2008; Kotsovilos et al., 2009; Mertens et al., 2012). Our study showed a high survival rate for short, wide-bodied one-piece implants in the posterior mandible. This was not surprising since it has been hypothesized that the functional area represented by the crestal bone surrounding the implant is substantially more important when considering the success and the failure of an implant than its overall length (Pierrisnard et al., 2003; Srinivasan et al., 2012). An increase in functional area is more dependent upon implant diameter than length. A wide diameter would result in an increased bone to implant contact, which enhances initial stability and the resistance of implants to stresses (Winkler et al., 2000). In our study all the posteriorly placed implants were 5mm in diameter, which may have reduced the stress on peri-implant crestal bone and consequently minimized crestal bone loss (das Neves et al., 2006; Renouard & Nisand, 2006). This is supported by finite element analysis, which indicates that occlusal forces are distributed primarily within crestal bone rather than along the entire length of implant; thus implant length is not linearly related to biomechanical stability (Meijer et al., 1992; Himmlova et al., 2004). We hypothesized that the use of two posterior implants combined with a single mid-symphysal implant would create a completely implant-supported overdenture rather than the more common approach of implant-and-mucosa supported overdenture. The posterior implants created a Kennedy III-type situation, as opposed to the distal extension Kennedy I-type situation (Feine et al., 2002; Carr et al., 2005). We expected that this tripodal design would reduce posterior bone resorption when compared to the more common distribution protocol with two to four inter-foraminal implants supporting the mandibular overdenture (Osman et al., 2013 a). This is particularly relevant for younger individuals where posterior bone resorption may become a critical issue with time.

We found a high failure rate of 42.1% for mid-palatal implants. Most failures occurred during the early healing phase (5 of the 8 failed implants, 62.5%). This is in accord with the two published studies that have reported outcomes for mid-palatal implants. Asscherickx et al. (2010) registered three early losses out of 34 mid-palatal implants during the initial healing
phase and none during the loading period. The authors attributed this to either parafunctional activity of the tongue or direct trauma from tooth brushing. These reasons were not considered applicable to our study since all the participants wore their relined dentures immediately after surgery, which shielded the palatal implants from direct trauma during the healing phase. Jung et al. (2012) reported the loss of 11 out of 239 mid-palatal implants (4.6%). Nine were lost during the healing phase and two under functional loading. The authors strongly linked this to the learning curve for mid-palatal implant surgery, suggesting that the short implant length may increase deflection of the implant axis during insertion, damaging the intra-bony threads and reducing primary stability; this was despite the high surgical expertise of all the surgeons involved in common implant surgery. Another cause for early implant failure may be related to the flapless technique we used for implant placement, related to increased thermal trauma to the bone due to limited irrigation during osteotomy preparation and possible deposition of epithelial or connective cells into the osteotomy site, which can interfere with osseointegration (Prithviraj et al., 2012). The failure incidences may also be related to bone quality in the mid-palatal region. Although recent work has shown adequate bone quantity and quality in the mid-palatal region to support implant placement (Siddiqi et al., 2012), there is little known about the risks of overheating bone in this anatomical site (Wiskott & Belser, 1999; Oh et al., 2002); a higher failure rate of implants in type I bone has been attributed to overheating during implant installation (Truhlar et al., 1997).

The late failures of palatal implants occurred in participants who also lost one or more of their crestal implants, suggesting that a patient-centered “cluster failure” effect may be partially responsible. Cluster failures can be related to local anatomic structure regarding bone quality and quantity, or to host-related factors such as the patients’ general health (Ekfeldt et al., 2001).

The results of a three dimensional finite element analysis comparing the stress/strain distribution in the peri-implant bone between the novel adopted implant distribution and conventional design used for overdentures support in the maxilla, revealed a substantial load bearing capacity for mid-palatal implants shared by the most distal implant on the loaded side (Osman et al., 2013 b). However, the recorded stress/strain values were within the physiological range of bone remodeling according to Frost’s Mechanostat theory (Frost, 1987). Thus, the question of whether the mechanical overloading has contributed to late implant failures or not remains debatable.
Fartash et al. (1995) reported marginal bone loss of 0.45mm around single crystal sapphire implants supporting mandibular overdentures during the first year of function. The survival rate of zirconia implants in our study (90.9%) was also close to that reported by Berge & Grønningsæter (2000) (92.1%) for single-piece sapphire implants supporting mandibular overdentures after one year. We suggest that ceramic implants generally and zirconia implants (Y-TZP) in particular can be clinically successful in this application, but their outcome is still inferior to the more established titanium implants when used for overdenture support.

The findings of this study are in accordance with conclusions made by Depprich et al. (2012) that zirconia implants are inferior to titanium ones with regard to survival and success rate. Further well-designed, long-term studies are needed to assess zirconia implants and provide a statement on their suitability as an alternative to titanium dental implants.

**CONCLUSIONS**

Based on the findings of this study, zirconia implants may be recommended for the support of overdentures. However, due to the increased marginal bone loss and higher fracture rate observed for zirconia implants compared to titanium implants, their use should only be limited to cases with allergy to titanium or those patients requesting a metal-free restoration. Future biomaterial science research should be directed towards producing surface characteristics on zirconia implants similar to those already established as the optimum for osseointegration of titanium implants. Design modifications are still needed to improve the biomechanical integrity of zirconia implants. Accurate diagnosis and treatment planning is of the utmost importance, particularly relevant in the maxilla where a higher failure rate was revealed compared to the mandible.
CHAPTER IV

Clinical and prosthodontic outcomes of ceramic implants supporting maxillary and mandibular overdentures

PART 2: Prosthodontic maintenance of attachment systems of overdentures on one-piece zirconia implants with novel distribution.

Publication status: Under Review

Osman, R.B., Duncan, W., Swain, Ma, S. Prosthodontic maintenance of maxillary and mandibular overdentures supported by zirconia and titanium implants featuring a novel implant distribution. Int J Prosthodont [under Review].
The aim of this study was to assess the prosthodontic maintenance requirements of maxillary and mandibular overdentures supported by one-piece zirconia implants in the context of novel implant distributions. Twenty-four edentulous participants (age 46 – 80 years) were randomly allocated to one-piece titanium (control) or zirconia (test) implant groups. Four maxillary implants (mid-palatal and three anterior crestal implants) and three mandibular implants (mid-symphysial and two bilateral distal implants) were surgically placed using a conventional loading protocol for an unsplinted prosthodontic design for participants. Overdentures in both jaws had similar attachment systems; ball abutment type patrices (diameter 2.25 – 3.1 mm) as parts of the one-piece implants and custom-made plastic matrices. Prosthodontic maintenance and success was documented during the first year of service. A total of 84 maintenance events were recorded for 19 participants. Three participants died: two in the control titanium and one in the zirconia test group. Two control participants dropped out. Three participants (one titanium; two zirconia) experienced early maxillary implant failures and had their overdentures converted to conventional dentures. Overdenture fracture was the primary maintenance event, especially for the mandibular prostheses. Three implants fractured in the zirconia test group. No significant differences were found in the prosthodontic maintenance between the two groups. Prosthodontic success determined using a six-field table analysis revealed no statistically significant difference between the groups. Removable overdentures on these one-piece zirconia implants with custom-made plastic attachment systems should not be used routinely in patients. On the contrary, they are recommended for patients needing or preferring a metal-free approach when being rehabilitated with implant overdentures. There is merit in the treatment concept with its novel implant distribution, although clinical trials with conventional two-piece titanium implants and maxillary or mandibular overdentures would be mandatory.
Maxillary and mandibular implant overdentures offer an established method of rehabilitating the predicament of edentulous patients using two-piece titanium implants and a variety of attachment systems (Zarb & Bolender, 2004; Payne & Zarb, 2013). Nonetheless, the key for sustained prosthodontic success is to minimize the burden of post-insertion maintenance (Payne & Solomons, 2000b; Çehreli et al., 2010; Osman et al., 2012a) and their cost implications over time (Watson et al., 2002; Heydecke et al., 2005).

Specifically, the first year of service following insertion of an overdenture on two-piece titanium implants is the proof-of-concept period with a series of anticipated early maintenance events, which reduce over subsequent years (Payne & Solomons, 2000a,b; Osman et al., 2012a; Watson et al., 2002; Den Dunnen, 1997; Bergendal & Enquist, 1998; Mackie et al., 2011a,b). Prosthodontic maintenance and complications are dependent on the implant overdenture designs (Payne & Solomons 2000b; Osman et al., 2012a). Current and historical debate has usually been related to either splinting the implants (usually with bars) or using unsplinted designs (usually with ball abutments) or more recently locator type attachments. This has been particularly relevant with maxillary implant overdentures (Mericske-Stern, 2003). Historical studies have confirmed prosthodontic maintenance issues in both academic and private practice settings (Dudic & Mericske-Stern, 2002; MacEntee et al., 2005; Naert et al., 2004; Nedir et al., 2006). Review of treatment outcomes for maxillary and mandibular implant overdentures show that this can be independent of the number of implants and the type of attachment system (Sadowsky, 2007). There are significant short and long-term maintenance requirements that patients must be aware of before selecting attachment systems, especially with the accumulative evidence for mandibular overdentures. Attachment systems play a significant influence on prosthodontic maintenance, particularly with regard to the type of matrices used (Rentsch-Kollar et al., 2010; Mackie et al., 2011a).

With the current practice and recommendations for usage of zirconia implants to address demands for “metal-free dentistry” and acknowledging rare cases of titanium allergy (Oliva et al., 2007; 2010b; Sicilia et al., 2008; Andreiotelli et al., 2009; Depprich et al., 2012; Payer et al., 2012; Javed et al., 2013), this treatment concept may also apply to implant overdentures (Osman et al., 2013 a). In the same way as single zirconia implants supporting crowns, this material’s unique properties necessitate a one-piece implant. Recommendations of novel distributions of these implants for maxillary and mandibular overdentures are, like two-piece...
titanium implants, subject to scrutiny of the outcomes of primarily implant success and secondarily prosthodontic success.

The aim of this study was to assess the prosthodontic maintenance requirements of maxillary and mandibular overdentures supported by one-piece zirconia implants in the context of novel implant distributions.

**MATERIALS AND METHODS**

**Participants**

Twenty-four edentulous participants (21 males; 3 females; age range 46 – 80 years, mean age 62.3 years) were recruited for a randomized controlled trial using both maxillary and mandibular implant overdentures. Ethical approval for the research was obtained from the Lower South Ethics Committee (LRS/09/06/023), New Zealand. Strict inclusion criteria for the participants included recurrent problems with their existing complete dentures and sufficient bone quantity in both jaws for implant placement. Exclusion criteria included any medical conditions contraindicating implant surgery, irradiated or bone-grafted jaws and any known metal allergies. Random allocation was then performed into two groups of 12 participants: a control group using one-piece titanium implants and a test group using one-piece zirconia implants. Titanium implants were manufactured from commercially pure titanium grade IV, whilst zirconia implants were made from yttrium-stabilized tetragonal poly-crystalline zirconia. Participants were to receive both maxillary and mandibular overdentures supported by either the titanium or zirconia implants.

**Surgical procedures**

Maxillary and mandibular one-piece titanium or zirconia implants including ball abutments (Southern Implants, Irene, South Africa) were placed surgically with open flap procedures for each group using a novel distribution (Fig 4.4a-d) (Osman et al., 2013 a). Each participant received a mid-palatal implant (Siddiqi et al., 2012) together with three crestal implants in the first premolar regions, following previous clinical trial protocols (Payne et al., 2004). The foundation for the novel distribution in the mandible was a mid-symphysisal implant similar to the mandibular single implant overdenture protocol (Alsabeeha et al., 2010; 2011) and bilateral distal implants similar to an implant-assisted mandibular bilateral distal extension removable partial denture treatment protocol (Wismeijer et al., 2013). A conventional healing period was followed.
Prosthodontics procedures

Each participant first received new diagnostic complete maxillary and mandibular dentures fabricated according to standardized prosthodontic protocol (Zarb et al., 2013). Participants wore their complete dentures for approximately eight weeks to allow adaptation. Following implant surgery, the intaglio surfaces of complete dentures were relieved and relined with a tissue conditioning material (Visco-gel, Dentsply). Closed-mouth impressions were made with polyether material (Impregum™ Penta™, 3M ESPE) to incorporate the respective custom-made matrices into the intaglio surface of the overdentures. An unsplinted prosthodontic design was used for all participants in both groups. The attachment systems comprised ball abutments (patrices) as part of the one-piece titanium or zirconia implants of different diameters. All maxillary implants had 2.25-mm patrices (Fig 4.4e), while mandibular implants had either 2.25-mm or 3.1-mm patrices (Fig 4.4f). The patrices were made of unalloyed grade 4 titanium with titanium nitride coating of 2.0 – 3.0 μm thick or yttrium-stabilized tetragonal polycrystalline zirconia (Y-TZP). The corresponding plastic resin matrices were made from polyoxymethylene copolymer.

Laboratory procedures were standardized with two experienced dental technicians using semi-adjustable articulators (Artex®, AmannGirrbach, Germany), acrylic denture teeth (Vita Physiodens for anterior and Vita Lingoform for posterior teeth), heat-cure denture base acrylic resin (WHW Universal Acrylic Denture Base, WHW Plastics, UK) and lingualized occlusion. No reinforcement of the dentures was done with any metal alloy framework. Delivery procedures of all implant overdentures were standardized (Payne & Zarb, 2013).
Figure 4.4 Clinical photos of control and test groups rehabilitated with implant overdentures supported by one-piece (a, c) titanium and (b, d) zirconia implants with (e, f) respective attachment systems

Prosthodontic maintenance and success

Post-insertion maintenance events during the first year were recorded and categorized (Payne et al., 2001a). Prosthodontic maintenance included adjustments and repairs either initiated following participants’ requests or professionally determined at recall appointments. Implant fractures/failures (ball abutment patrix maintenance), maintenance of matrices, overdenture fractures, acrylic denture teeth fractures, peri-implant mucosal enlargements (hyperplasia) (Payne et al., 2001b), and relines/remakes of overdentures were all documented.
Overdenture adjustments recorded in association with peri-implant mucosal enlargement (hyperplasia) were not reported as a separate entity.

Implant fractures/failure that occurred after commencement of prosthodontic procedures were accounted for and recorded, since the patrices were part of the one-piece implants. This included implants that were successfully osseointegrated, but prosthodontic procedures could not be performed due to deep implant placement and lack of access to the ball abutment. Therefore, from a prosthodontic point of view, these implants were considered as failed implants because of an inability to replace the patrix component, unlike the case with two-piece implants.

The need for relining the overdenture was assessed according to one or more of the following specific criteria: need for matrix replacement, lack of stability in the antero-posterior direction and participant complaints of increased food retention underneath the overdenture. Replacement of an individual matrix did not involve a reline impression and was directly attached chair-side using cold-cure acrylic resin. Participants were subsequently assigned to one of six objectively defined outcome fields: success, survival, unknown, dead, retreatment (repair) and retreatment (replace). A limit of two replacements of matrices per implant in the first year, and no more than one reline of the overdenture were used as a criterion to allocate the participant to the field of success. More than two matrix replacements, or more than one overdenture reline would allocate the patient to the retreatment (repair) field. If part or the entire overdenture was no longer serviceable due to the loss of implants or irreparable mechanical breakdown, replacement prosthesis was deemed necessary. In addition, the pre-insertion maintenance events that occurred during the healing phase were also reported.

**Statistical analysis**

Prosthodontic maintenance data were analyzed using SPSS version 17.0 (SPSS Inc., Chicago, USA) and level of statistical significance was set at $P<0.05$. Chi-square test was used to analyze categorical dependent variables and to compare the prosthodontic success between two groups. The maintenance requirements were compared between titanium and zirconia implant overdentures. The data were also compared between two jaws.
RESULTS

Three participants died during the study period, two in the titanium group and one in the zirconia group. Two participants in the titanium group dropped out and further three participants (one in the titanium and two in the zirconia) had early maxillary implant failures and had to be converted to conventional complete dentures. Maintenance events were recorded for 19 participants for one year.

Eleven participants (55%) experienced prosthodontic maintenance events during the healing period prior to loading (Table 4.15). Three major maintenance categories emerged namely, overdenture fracture, denture tooth fracture/dislodgement and peri-implant mucosal enlargement that necessitated excision prior to impression making.

Table 4.15 Individual and Combined Pre-insertion Prosthodontic Maintenance Events

<table>
<thead>
<tr>
<th>Category</th>
<th>No. of maintenance events per implant type/arch</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Titanium</td>
</tr>
<tr>
<td></td>
<td>All maintenance events* (n = 19)</td>
</tr>
<tr>
<td>Fractured overdentures, puncture fracture,</td>
<td>11</td>
</tr>
<tr>
<td>fractured denture teeth</td>
<td>3</td>
</tr>
<tr>
<td>Peri-implant mucosal enlargement</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>

* For both maxillary and mandibular overdentures
n = No. of participants

Prosthodontic maintenance

A total of 84 maintenance events were recorded after one year. Three implant fractures were recorded in the zirconia group; one in the mandible while the other two were crestal maxillary implants. In addition, two mid-palatal implants and a mandibular posterior implant, which were successfully osseointegrated could not be used due to their deep placement.
The most prominent maintenance event encountered was overdenture fracture (Table 4.16). The fractures usually involved the acrylic resin around the clip. Overdenture fractures occurred on 19 occasions in nine different patients of which the majority concerned mandibular bases (15 occasions). Out of the 15 fracture events recorded for mandibular implant overdentures, five participants experienced repeated fractures of their prostheses within the range of 2 to 3 times, which influenced the data. On comparing the fracture events between titanium and zirconia implant overdentures, irrespective of the arch, no significant difference was found. Other maintenance events included replacement of worn or dislodged matrices, repair of chipped or dislodged acrylic denture teeth and relining of overdentures. There were no significant differences between the titanium and zirconia implant overdentures regardless of jaws. Worn matrices were encountered in three participants, only in the zirconia group. Two participants experienced wear of maxillary clips whereas the other participant experienced the opposite. Individual matrix replacement was encountered in cases where patrices of different sizes were employed. This was common in mandibles where a small diameter mid-symphysal ball abutment ($\varnothing$ 2.25 mm) was used in combination with larger distal ones ($\varnothing$ 3.1 mm). In all of these cases, the participants presented with the complaint of unstable denture around the mid-symphysal implant which necessitated replacement of the clip according to direct attachment incorporation technique. The most prominent biological complication recorded was peri-implant mucosal enlargement. Most of the peri-implant mucosal enlargement cases were associated with implants placed in ridges featuring limited amount of attached gingiva and highly reduced bone height (accommodating a minimum of 6-mm implant length). Other cases were observed around mid-palatal implants.
Table 4.16 Individual Post-insertion Prosthodontic Maintenance Events per Group

<table>
<thead>
<tr>
<th>Category</th>
<th>All maintenance events* (n = 19)</th>
<th>Titanium</th>
<th>Zirconia</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maxilla (n = 8)</td>
<td>Mandible (n = 8)</td>
<td>Maxilla (n = 11)</td>
</tr>
<tr>
<td><em>Patrix fractured</em></td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><em>Dislodged, worn, loose matrix/ housing</em></td>
<td>18</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td><em>Matrix replaced</em></td>
<td>25</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td><em>Fractured overdentures, puncture fracture, fractured denture teeth</em></td>
<td>26</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td><em>Reline</em></td>
<td>4</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td><em>New implant overdenture constructed</em></td>
<td>3</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td><em>Peri-implant mucosal enlargement</em></td>
<td>5</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>37</strong></td>
<td><strong>16</strong></td>
<td><strong>21</strong></td>
</tr>
</tbody>
</table>

* For both maxillary and mandibular overdentures
n = No. of participants

Prosthodontic success

A six-field analysis of prosthodontic success for the patients after one year was documented (Table 4.17) (Payne et al., 2001a). No significant difference was found in any of the fields of prosthodontic success when comparing titanium and zirconia groups. Half of patients in both titanium and zirconia groups were allocated to retreatment (repair) field. The high incidences of repair were mainly due to fractured overdenture events and partially due to dislodged or fractured denture teeth. This negatively impacted the prosthodontic success rates for these two groups with corresponding figures of 8.3% and 25% recorded for titanium and zirconia implant overdentures respectively. Three events (one in titanium and two in zirconia group) in the retreatment (replace) were due to the maxillary implant failures and subsequent conversion to conventional complete dentures. No significant difference was found in any of the fields of prosthodontic success when comparing titanium and zirconia groups.
**Table 4.17 Prosthodontic Success: Six-Field Table Analysis**

<table>
<thead>
<tr>
<th></th>
<th>Titanium (n=12)</th>
<th>Zirconia (n=12)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Success</strong></td>
<td>1 (8.3%)</td>
<td>3 (25%)</td>
</tr>
<tr>
<td><strong>Survival</strong></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Unknown</strong></td>
<td>2 (16.7%)</td>
<td>0</td>
</tr>
<tr>
<td><strong>Dead</strong></td>
<td>2 (16.7%)</td>
<td>1 (8.3%)</td>
</tr>
<tr>
<td><strong>Retreatment (repair)</strong></td>
<td>6 (50%)</td>
<td>6 (50%)</td>
</tr>
<tr>
<td><strong>Retreatment (replace)</strong></td>
<td>1 (8.3%)</td>
<td>2 (16.7%)</td>
</tr>
</tbody>
</table>

n = No. of participants

**DISCUSSION**

This research presents prosthodontic maintenance requirements of maxillary and mandibular implant overdentures on titanium and zirconia one-piece implants using an unsplinted design. The new approach is undoubtedly controversial. Comparison of the outcomes of this study to other trials that used two-piece titanium implants is problematic. It is also acknowledged that there was a significant drawback from a prosthodontic perspective using zirconia implants as a one-piece implant. The small patient cohort implies that stringent patient selection was required. As is not uncommon for human clinical trials involving new interventions, we had unequal group sizes and the short observation period of only one year (Naert et al., 2004; Attard & Zarb, 2004; Alsabeeha et al., 2011). However, our standardized implant design, implant distribution, prosthodontic/laboratory procedures and status of the opposing arch are pertinent.

There are a number of findings that are a source of concern for further investigation and improvement. Firstly, the fracture rate of zirconia implants raises the question of whether zirconia implants exhibit sufficient mechanical properties to support overdentures. Secondly, there was an increased tendency of matrix wear observed in zirconia group linked to the physical and chemical properties of the implant type used. The novel implant protocol influenced the prosthodontic outcomes of both the maxillary and mandibular overdentures and could also be applied for patients treated with conventional two-piece titanium implants.

Wear and tear of attachment systems are known to be the most prevalent maintenance requirement for any type of implant overdenture. This includes matrix loosening, matrix replacement or activation to restore lost retention or a damaged retention mechanism (Walton,
2003; MacEntee et al., 2005; Çehreli et al., 2010; Kleis et al., 2010; Chen et al., 2013). Our most frequent mechanical complication in the current research was overdenture fracture, which was different to other related implant overdenture literature. It has been suggested that with the mandibular two-implant overdenture design, the prosthesis rotates around an anterior fulcrum line or hinge-axis (Kimoto et al., 2009). These movements can clinically lead to plastic or permanent deformation of the matrix, resulting in a reduction of retentive forces or fractures of the matrices. Our novel implant distributions reduced rotational overdenture movements, particularly in the mandible and thus reducing wear of the attachment systems. The distal implants in the mandibular design created a Kennedy III-type situation, as opposed to anterior inter-foraminal implants being in a Kennedy I-type situation. In the maxillary design, the most anteriorly positioned implant depending on the force direction will act as an indirect retainer minimizing the tissue-ward movement of the prosthesis when occlusal dislodging forces are applied (Carr et al., 2005; Osman et al., 2013a). Furthermore, though not statistically significant, the difference in the rate of matrix wear between the titanium and zirconia implant groups is more suggestive of the difference in the implant material as a possible etiological factor. Zirconia is a much harder material than titanium and more liable to intra-oral aging with a subsequent increase in its surface roughness (Piconi & Maccauro, 1999). This may have contributed to the wear of matrices. An x-ray diffraction and scanning electron microscopy analysis is being conducted on retrieved failed zirconia implants to support or refute the latter claim, the results of which will be published elsewhere. In addition, randomized controlled trials with a larger sample size are also recommended to investigate whether there is a statistically significant difference in prosthodontic maintenance between titanium and zirconia implant overdentures. In light of all matrix replacement events being observed in cases featuring different matrix size, the differences in abutment size may be suggested as a possible etiological factor. Following the surgical implant placement at the same level, the smaller sized mid-symphysyeal ball abutment would be closer to the gingival margin than the two larger distal abutments. This might have prevented the accurate recording and transferring of location of the smaller mid-symphysyeal abutment on the cast. Therefore, it may be advisable that same sized ball abutments are used when the novel mandibular implant distribution is employed.

We did not use a high impact resin, which may have affected the incidence of overdenture fractures. Considering the frequent observation of overdenture fracture, we recommend the use of either high impact resin or a cobalt-chrome base in overdentures using this type of novel distribution. However, it must be noted that the possibility of minimizing long-term
maintenance issues should be weighed against the burden of additional cost to the patients. Reports of overdenture fractures have been attributed to the large space occupied by the abutment and retentive components thus reducing acrylic thickness surrounding the attachment systems (Jemt et al., 1992; Watson et al., 1997; Widbom et al., 2005). The acrylic resin part of the implant overdenture has been found as the weakest link in the fabrication and therefore alternative materials such as metal alloy framework have been suggested to reinforce the prosthesis and minimize such complication (Kramer et al., 1992; Mericske-Stern, 1998; Smedberg et al., 1999; Dudic & Mericske-Stern, 2002; Krennmair et al., 2008). However, the evidence may not be strong enough to justify the cost of metal reinforcement and the possibility of increased implant loading has been mentioned (Davis & Packer, 1999; Kiener et al., 2001; Walton et al., 2002). Nevertheless, with the novel protocol, metal reinforcement may be used without the fear of implant overloading as the increased implant number will allow the load to be more widely distributed thus improving the biomechanical situation (Sahin et al., 2002). However, further research in this area is still required before any definite recommendations can be made. The possible use of fiber-reinforced denture bases to improve the mechanical strength of prostheses has also been suggested (Vallittu, 1996; Rachad et al., 2011). A number of studies reported increased fracture incidences of maxillary overdentures compared to those in the mandible. This is not in agreement with the findings of the current study where the majority of fracture incidences were reported for the mandible (15 events) compared to the maxilla (4 events). This can be explained on the basis that most of studies from which the conclusions were drawn used bar-retained overdentures, which might have resulted in reduced bulk of acrylic resin to accommodate the attachment system resulting in higher stresses within the acrylic and a high fracture incidence. Conversely, in our study the smaller diameter ball abutments used in case of maxillary overdentures compared to their mandibular counterpart might have prevented the occurrence of such complication. It is noteworthy that out of 15 fracture events encountered in mandibular overdentures, two patients dropped their dentures while cleaning them. Five patients experienced repeated fracture events of their overdentures within the range of 2 to 6 times which reflects the results reported by Tolman & Laney (1992) that mechanical problems tend to be repetitive in the same patients.

Several studies have reported abutment screw-loosening as one of the common prosthodontic complications with maxillary and mandibular overdentures (Jemt et al., 1992; Chan et al., 1995; Davis & Packer, 1999; Naert et al., 2004; Andreiotelli et al., 2010). Screw loosening causes inconvenience to the patient and practitioner. Furthermore, it can be
financially burdensome if it occurs frequently. Despite the acknowledged drawback associated with the one-piece implant system such a design allowed the avoidance of such complication with its subsequent time and cost implications.

Fracture of implants is a rare complication and is reported to occur in 0.2% to 3.8% of implants supporting overdentures over 5- to 8-year follow-up period (Buser et al., 1997; Davis & Packer, 1999). However, in the current study a higher fracture rate (2.6%) was observed where three out of 98 titanium and zirconia implants that were still in function at the end of the one-year follow-up period fractured. All of the fractured implants were in the zirconia group and fractured almost half way along the implant length. In one case, the patient exhibited limited manual dexterity and reported difficulty in manipulating his mandibular overdenture. Unfavorable bending moments created by the patient’s attempts to dislodge the overdenture associated with corono-apical bone resorption and loss of supporting bone is suggested as the most probable cause for the implant fracture (Rangert et al., 1995). Thus, pre-operative evaluation of patient’s manual dexterity cannot be overemphasized particularly when one-piece zirconia implants are employed for overdenture support. Another factor, which may have further contributed to implant fracture, is the small implant diameter (Ø 3.75 mm). A literature review on fracture of oral implants pointed to implant size (diameter) as one of the influential factors with a higher tendency of smaller diameter implants to fracture compared to larger ones (Tagger Green et al., 2002).

In the other two instances, a mid-palatal and an off-center crestal implant failed resulting in a maxillary overdenture being supported by two anterior implants in the premolar region bilaterally. The geometry of the two remaining implants being arranged in a straight line would allow for bending to occur as a result of the resultant lateral occlusal component which might have led to failure of the remaining implants (Rangert et al., 1995). Therefore, it may be concluded that a minimum number of four implants is a prerequisite when zirconia implants are employed for maxillary overdenture support. In clinical situations where implant failures resulted in a reduced implant number, resilient liner-retained rather than a clip-retained overdenture can be considered to optimize load distribution and significantly reduce vertical and horizontal bone loss. The higher incidence of implant fracture within the zirconia group compared to the titanium one lend support to the wide spread notion among the clinicians and the patients that ceramics are mechanically inferior to metals as an implant material (Kohal et al., 2009a). This outcome was probably contributed to by the identical
design of the zirconia implants to those of the titanium and insufficient attention to design optimization for the ceramic.

The need for relining mandibular implant overdentures has been reported to vary from 8 to 30\% regardless of the design (Payne & Solomons, 2000b). A number of studies have reported reline rates to be more prominent with resilient attachments (ball anchors or a round clip bar) compared to more rigid type attachments (U-shaped bar or rigid telescopic attachments) (Dudic & Mericske-Stern, 2002). Resilient attachment systems used in mandibular two-implant overdentures are claimed to transfer undesirable forces to the denture-bearing tissues resulting in resorption, which makes relining necessary (Jacobs et al., 1992; Schmitt & Zarb, 1998; Wright et al., 2002). In the current study, a delayed bone resorption rate can be expected when compared with the commonly used 2 to 4 inter-foraminal implant overdenture design. The Kennedy class III situation created with novel mandibular design is expected to eliminate the antero-posterior rotation of denture around the anterior fulcrum line thus preserving the integrity of the distal bearing tissues (Carr et al., 2005; Osman et al., 2013 a).

Jemt and colleagues (1992) found that in the case of bar-retained maxillary implant overdentures, denture base relining was needed for 24\% of cases during the first year of function to compensate for the residual ridge resorption under the distal extension areas. The influence of opposing dentition and number of implants per patient on reline rate was not mentioned and thus could not be evaluated. In the current study, reline for maxillary overdentures supported by either titanium or zirconia implants was reported for only 5.7\% of the patients at the 1-year follow-up. Following the biomechanical principles applied for partial removable prosthodontics, the novel design resulted in an increased number of fulcrum lines (Osman et al., 2013 a). The most anteriorly positioned implant depending on the force direction acted as an indirect retainer minimizing the tissue-ward movement of the prosthesis when occlusal dislodging forces were applied.

Clinically short maxillary abutments have been used to reduce the bulkiness of the maxillary overdenture (Jemt et al., 1992; Johns et al., 1992). This approach would compromise the access for oral hygiene and development of an optimal oral maintenance protocol, which would encourage the development of hyperplasia. The same explanation can be extrapolated to cases of mucosal enlargement around mid-palatal implants. Mid-palatal implants featured small ball abutments (Ø 2.25 mm) close to the gingival margin, which may
have interfered with oral hygiene measures. Thus clinically, it is important to elevate the
shoulder of the implant and ball abutment above the mucosa to avoid such a problem
(Klemetti et al., 2003). For cases with reduced amount of attached gingiva and limited ridge
height, the mobile gingiva is postulated to be less resistant to mechanical irritation, such as
tooth brushing, which may affect cleaning procedures and make tissues more susceptible to
inflammation (Mericske-Stern et al., 1994). No cases of decubitus ulcers were recorded and
this can be attributed to the novel implant distribution as the mandibular overdentures were
mainly implant-supported rather than mucosa-implant supported. In the case of the maxilla,
the increased number of fulcrum lines limited overdenture rotation and minimized the
incidence of soft tissue complications (Osman et al., 2013 a).

Finally, we propose that it is possible to selectively use one-piece zirconia implants to
support overdentures in patients with a preference for a metal-free approach or for those with
an allergy to titanium. We have found positive experiences with participants towards
overdentures on zirconia implants perceiving them to be “healthier, more natural, and closer
to bone in qualities” (Osman et al., 2012b). There is also merit in the treatment concept with
its novel implant distribution, although similar clinical trials with conventional two-piece
titanium implants and maxillary or mandibular overdentures would be mandatory.

CONCLUSIONS

Removable overdentures on one-piece zirconia implants with custom-made plastic
attachment systems should not be used routinely in patients. On the contrary, they are
recommended for patients preferring a metal-free approach when being rehabilitated with
implant overdentures.
CHAPTER V

Fractographic analysis of fractured zirconia implants

Fractured Zirconia Implants and Related Implant designs: Scanning Electron Microscopy Analysis

Publication status: Published

ABSTRACT

Two fractured one-piece experimental (commercially unavailable) zirconia implants were analyzed using scanning electron microscope (SEM) analysis to identify failure origins and aid in understanding the failure mechanisms. Modifications to the zirconia implant design are suggested to minimize such fracture incidences. Two zirconia implants fractured during the final torquing in the maxillary ridge using the prescribed hand torque wrench. The implants were subsequently retrieved and prepared for optical and SEM evaluation. Critical attention was given to the fractography (crack morphology) of the fractured implants to identify the fracture origin. Events related to initiation and propagation of the crack front could be detected from the morphology of the fractured surfaces. Unfavorable torque and bending forces applied on the implant during surgical placement and the inherent flaws in the material may have resulted in crack initiation and implant failure. Caution must be exercised when placing zirconia implants in dense bone sites. Modification of surgical protocols for the intended implant site may be necessary. Improvement in design features specific to zirconia implants, and strict quality control during manufacture is essential to minimize the likelihood of fracture.
Zirconia has attracted considerable interest due to its favorable esthetic results, mechanical strength and toughness, coupled with a Young’s modulus of the same magnitude as stainless steel (Heydecke et al., 1999; Denry & Kelly, 2008). Zirconia has a Young’s modulus of 200 GPa, Poisson’s ratio of 0.31, and ultimate tensile strength of up to 1400 MPa (Piconi & Maccauro, 1999; Denry & Kelly, 2008). The use of zirconia as restorative components has been widely cited in the literature; however, yttrium-stabilized tetragonal zirconia polycrystal (Y-TZP) has yet to be established as the material of choice for endosseous oral implants (Kohal et al., 2008; Wenz et al., 2008; Özkurt & Kazazoğlu, 2011).

Zirconia implants have been shown to be capable of withstanding oral forces over an extended period of time (Akagawa et al., 1993, 1998; Kohal et al., 2004). Histologic and animal studies have revealed comparable rates of osseointegration to titanium implants that have similar surface characteristics (Scarano et al., 2003; Kohal et al., 2004; Sennerby et al., 2005). Although the prevalence of allergy to titanium is low (0.6%), it has been implicated in some cases of implant failure, and zirconia implants have been proposed as an alternative for such patients (Sicilia et al., 2008; Siddiqi et al., 2011; Javed et al., 2013).

Macroscopic and microscopic designs of oral implants are crucial in the success of osseointegration and the longevity of implants (Brunski, 1988; Steigenga et al., 2003; Wennerberg & Albrektsson, 2009; Abuhussein et al., 2010). Given the brittle nature of ceramic, optimizing the design of zirconia implants is a prerequisite not only to improve osseointegration but also to ensure the mechanical integrity of the implant at the time of placement and during subsequent functional loading. Macroscopic aspects such as implant length, diameter and body geometry as well as different thread parameters including depth, thickness, pitch, shape, and face angle must be analyzed to ensure the most optimal biomechanical property (Steigenga et al., 2003, 2004; Hall et al., 2005; Vandeweghe et al., 2010).

The fracture of oral implants is a rare occurrence with a reported incidence ranging between 0% and 3.4% (Green et al., 2002; Velasquez-Plata et al., 2002). Potential causes that have been suggested include bending overload, manufacturing imperfections, insufficient biomechanical designs, prosthesis misfit, loss of support due to bone resorption, and parafunctional habits (Green et al., 2002; Virdee & Bishop, 2007). However, such reports are
confined to titanium implants after a considerable period of functional loading (Green et al., 2002; Velasquez-Plata et al., 2002; Virdee & Bishop, 2007; Manda et al., 2009). Fracture of zirconia implants has recently been reported with a rate of 10% after a mean post-loading period of 36 months (Gahlert et al., 2012b). A recent systematic review found that reports of zirconia implant fractures are scarce (Andreiotelli et al., 2009); to date, fracture of one-piece zirconia implant at the time of placement does not appear to have been reported.

The aim of this study was to investigate the causes of fracture of Y-TZP implants during surgical placement and to suggest design modifications to minimize such incidences.

MATERIAL AND METHODS

From November 2009 to July 2011, a total of 37 one-piece experimental (commercially unavailable) zirconia implants (Southern Implants, Irene, South Africa) were placed in 12 completely edentulous participants to support maxillary overdentures (Fig. 5.1). This was a part of randomized clinical trial evaluating clinical and prosthodontic outcomes of ceramic implants supporting maxillary and mandibular overdentures. Ethical approval was obtained from the Lower South Regional Ethics Committee for this randomized controlled trial. The zirconia implants consisted of 95% zirconia with yttria and alumina making up the remaining 5%. The one-piece zirconia implants varied in diameter and length according to the site of implant placement that was either within the anterior maxillary crestal ridge or mid-palatal region. The diameter of crestal implants was 3.8 mm with a length of either 10 or 11.5 mm, whereas the diameter of mid-palatal implant was 5 mm with a length of either 6 or 8 mm. Both types of zirconia implants had a 2.25 mm diameter ball abutment. Both implants had the same thread configuration of a 0.6 mm pitch and a 0.1 mm width. The crestal implant had a 0.3 mm pitch depth, whereas the mid-palatal implant had a 0.5 mm depth (Fig. 5.2).
Two of the 37 implants (5.4%) fractured during surgical placement. Surgical sites were the mid-palatal (Ø5 X 8 mm) and previously tooth 21 region (Ø 3.8 X 11.5 mm implant), which were subjectively determined as type I and II bone quality, respectively (Lekholm & Zarb 1985). Both fractures occurred during the final torquing of the implants using the recommended hand torque wrench. Using a surgical trephine, the fractured implants were retrieved; however, the apical one-third of the mid-palatal implant could not be safely removed and was left buried. A replacement mid-palatal implant was subsequently placed anterior to the intended site. The fractured implants were examined under a light microscope.
to establish the path of fracture. The implants were then ultrasonically cleaned in 96% isopropanol for 20 min and subsequently washed for 5 min in distilled water. The samples were dried before sputter-coating with gold-palladium resulting in a layer thickness of less than 50 nm. Analysis using a scanning electron microscope (SEM) (Cambridge Scanning Company Ltd., Barhill, UK) at an electrode voltage of 8 kV was performed at a magnification range of 10–800 x. Details of the shape of the implant, such as the thread depth and width in the vicinity of the fracture origin and thread systems were recorded and measured.

RESULTS

Scanning electron microscope images of the crestal implant at a low magnification (Fig. 5.3a) showed that the implant fracture occurred at the junction of the external hex and the shoulder of the implant. Some chipped threads along the body of the implant were also detected. The fractured surface revealed two twisted cracks separated by a smooth fractured region. On one side, the crack deflected and propagated down in a spiral manner to the level of the first implant thread (Fig. 5.3b; solid arrows), whereas the crack on the other side arrested at the junction of the hex and the shoulder of implant (Fig. 5.3b; dotted arrows) resulting in a relatively flat fractured surface.

Figure 5.3. Low magnification (10x) scanning electron microscope (SEM) images of fractured crestal implant. (a) Crack initiating at the level of the implant hex for torquing tool attachment; (b) Higher magnification (25x) view of fractured surface. Solid arrows point to crack on torsion side; Dotted arrows point to relatively flat fracture on flexure side.

Under a higher magnification, a relatively smooth region surrounding the fracture origin also known as mirror could be detected (Fig. 5.4). In this region, the crack deflection/branching and the crack front remained relatively planar and featureless. Lines (hackles) on the fractured surface running parallel to the direction of the crack propagation were noted
(Fig. 5.4b). The direction of a mirror hackle boundary with the hackle lines originated on the concave side of mirror (Figs 5.4 and 5.5), and clearly defined arrest lines were observed (Fig. 5.4). There was increased fragmentation at the fracture site (Fig. 5.5), and the polycrystalline micro-structural nature of zirconia obscured the mist region. Adjacent to the main fracture, some secondary cracks could be identified (Figs 5.4 and 5.6).

Figure 5.4. Features of fractured surface. (a) Fracture mirror (Mir) (magnification factor = 400x) and secondary cracks, (b) Arrest lines (Ar), hackle lines (magnification factor = 800x).

Figure 5.5. Dotted arrows pointing to the direction of crack propagation. Solid arrows pointing to the crack fragmentation (magnification factor = 40x).

Figure 5.6. Arrows pointing to secondary cracks at the junction of hex and shoulder of implant. (a) Lower magnification (35X); (b) Higher magnification (520X).
The mid-palatal implant showed a 360° spiral fracture extending from the third thread and propagating downwards almost parallel to the edge of the implant before cleaving the implant into two parts (Fig. 5.7). Scanning electron microscope images under higher magnifications showed hackle features that appeared to initiate at the junction of the thread with the implant body, just adjacent to the lower end of the flute (white oval highlighted area in Fig. 5.8a). A fracture mirror region could not be detected (Fig. 5.8b). The hackle lines were traced back to the sharp base of the thread (Fig. 5.8 b&c) and a higher magnification of the site also showed micron-level machining cracks (Fig. 5.8c).

Figure 5.7. Clinical and scanning electron microscope (SEM) images of fractured mid-palatal implant. (a) Retrieved coronal two-third of the implant after fracture; (b) Replacement implant (r) placed more anteriorly to the intended site; (c) Crack propagation initiating from the third thread (magnification factor = 10x) and (d) Implant rotated 90° clockwise to show the spiral pattern of fracture (magnification factor = 10x)
Figure 5.8. (a) Overview of the fractured implant with the white oval area indicating the origin of the failure. The black arrows point out the sharp notches at the base of the machined thread representing areas of high stress concentration (magnification factor = 25x); (b) A close-up view of the white highlighted area in (a) showing the hackle lines initiating from the base of the sharp thread edge and probable origin of crack initiation (magnification factor = 250x) and (c) White dotted area marks minute machining cracks suspected of being crack origin (magnification factor = 500x).

**DISCUSSION**

The purpose of this report was to analyze the fracture surfaces of one-piece zirconia implants to aid in understanding of failure mechanisms and to improve the design of zirconia implants. Events related to initiation and propagation of the crack front during failure could be traced through the morphology of fracture surfaces (Scherrer et al., 2006) and was therefore considered in detail for each implant. Observations based on a limited number of samples do not permit definition of a general trend; however, this report may provide a useful insight into the mechanical behavior of zirconia implants that may minimize such incidences in the future.
The SEM images of the crestal implant showed that the implant fracture occurred at the junction of the hex and the shoulder of the implant as observed by the smooth region known as mirror. This may be the site of the crack initiation, as in this region, the crack velocity would be too low to cause any crack deflection/branching, and the crack front would therefore remain relatively planar and featureless.

The zirconia implants in this study were unavoidably subjected to bending and torquing forces during placement. The torque applied to the implant was not only purely rotational but was also combined with a vertical loading by the hand torque wrench that formed a levering effect at the coronal portion of the implant. This type of superimposition of torsional and bending moments corresponds to twist hackle, which was observed during the SEM analysis (Fig. 5.4b) (Scherrer et al., 2006). The small mirror size (Quinn, 2007) and the increased fragmentation at the fracture site are indications of high stress at fracture (Quinn et al., 2005) (Fig. 5.5). The length of the torque wrench may have resulted in a high bending moment that may have been sufficient to fracture the implants. Some chipped threads along the body of the implant may have occurred during its retrieval with a surgical trephine.

The direction of a mirror-hackle boundary with the hackle lines originating on the concave side of mirror indicated that the direction of crack propagation originated from the external surface and radiated internally (Figs. 5.4 and 5.5). The clearly defined arrest lines observed in SEM images suggests that the crack propagated internally in steps of a decreasing stress field (Fig. 5.4).

Scanning electron microscope images of the mid-palatal implant under higher magnifications showed hackle lines that appeared to initiate at the junction of the thread with the implant body, just adjacent to the lower end of the flute (white oval highlighted area in Fig. 5.8a). A fracture mirror region could not be detected, which meant that there were some considerable torque forces, causing the crack to follow a complex path (Quinn, 2007). In the absence of any other well-defined features on the fracture surface, the hackle lines were the only indicator to determine the origin and direction of the crack propagation (Fig. 5.8b). One of the causes of mid-palatal implant fracture may have been the difficult direct access of the torque wrench to the site due to the anatomic consideration and additional factor of dense bone quality of the mid-palatal region, resulting in further levering against the implant and contributing to the excessive bending forces on the implant. This may have been avoided by
slight over-preparation of the implant site when dealing with a dense bone, so that the need for hand torquing of zirconia implants is minimized.

Additional features such as the implant design and manufacturing imperfections may also have contributed to its fracture. Microscopic surface treatment and its inadvertent flaws have been suggested as potential causes of implant fracture. However, different analyses of fractured titanium implants have shown that defects associated with the manufacturer’s design and production are the least likely reasons for implant fracture (Eckert et al., 2000; Velasquez-Plata et al., 2002). With zirconia implants, the situation is slightly different as surface modifications and surface flaws may compromise the shear and tensile strength of ceramic implants and lead to early failure (Andreiotelli & Kohal, 2009). This is evident in the case of the mid-palatal implant where micron-level machining defects were found in close association with the suspected crack initiation site, which were probably caused by the diamond grit of the milling lathe and parallel to the grinding direction (Fig. 5.8c). Such cracks combined with the high stress concentration areas created by the sharp thread edge could be implicated as the reason for catastrophic implant fracture. This finding is in agreement with Kelly et al. (1989) who reported that fracture of ceramics are usually initiated at locations involving surface porosities and cracks. These flaws might have acted as nidi for crack propagation. This emphasizes the importance of a strict quality control manufacturing process to reduce the incidence of such occurrence and improve clinical outcome of zirconia implants.

The configuration of the thread design is another significant contributing factor in the fracture of the implants during surgical placement. Sharp threads as well as internal line angles at the junction of the thread with implant body allow for focal areas of high stress concentration leading to fracture (Piattelli et al., 1998). The relatively deep thread depth of 0.5 mm, as seen in the mid-palatal implant used in the current study, would contribute to a higher stress concentration at the base of the notch well beyond that generated by the inadvertent bending moments applied with the hand torque wrench during implant placement. Furthermore, rapid clearance of bone debris hindered by such thread depth would add further torque resistance during the implant placement especially in the case of dense bone (Steigenga et al., 2003). Therefore, a thread design for zirconia implants involving filleting of internal line, increased thread width, and decreased thread depth is suggested to improve its biomechanical integrity. It is also suggested that the flute dimensions be kept to a minimum, thus maximizing implant dimensions and strength in implants made of this brittle material.
CONCLUSIONS

Fracture of zirconia implants, either at surgical placement or during subsequent function, is a relatively recent topic that merits further investigation. In this report, the incidence of implant fracture during surgical placement could be attributed to the steep learning curve of surgeons as well as various implant design aspects. Caution must be exerted when using zirconia implants in high density bone sites and modification of surgical protocols may be necessary to minimize the need for hand-torquing. Design features and surface modifications specific to zirconia implants and strict quality control of the manufacturing process are needed. Routine clinical application of zirconia implants must therefore be supported by further long-term clinical trials.
CHAPTER VI

Patient perspectives of Novel Implant Overdenture Treatment

Patients’ perspectives on zirconia and titanium implants with a novel distribution supporting maxillary and mandibular overdentures: A qualitative study.

Publication status: Published

ABSTRACT

This qualitative study explored the perceptions of edentulous patients regarding their rehabilitation with maxillary and mandibular implant-supported overdentures employing a protocol that featured novel implant sites and distribution. In-depth semi-structured interviews were conducted with 16 participants who have taken part in a randomized controlled trial. Each received implant overdentures supported by either titanium or zirconia one-piece implants. Participants received 4 implants in the maxilla and 3 implants in the mandible. The implant distribution was: in the maxilla, a mid-palatal implant and three anterior implants in the incisor and first premolar regions; in the mandible, a mid-symphysis implant and bilateral distal implants in the first molar region. All interviews were conducted by a researcher not involved with the clinical aspect of the randomized controlled trial and were transcribed verbatim and analyzed using a thematic inductive analysis approach. The perceived advantages of the treatment were functional improvement and increased social confidence. Cost was a significant barrier for edentulous patients seeking implant treatment. Previous experience with complete dentures, age and length of treatment were further factors that influenced decisions regarding prosthodontic rehabilitation. The novel implant protocol was acceptable to patients. Implant overdentures improve the quality of life of edentulous patients. Acceptance of dental implants may be increased by mitigating the cost of treatment. The mid-palatal implant site may be a potential alternative to extensive surgical procedures during the prosthodontic rehabilitation of atrophic maxillary ridges. The mandibular design offers patients the advantages of a removable prosthesis with increased retention.
Removable implant-supported overdentures have become a widely accepted and well-established treatment option for edentulous patients (Zarb, 2004). Patients experience enhanced retention, stability, masticatory efficiency and an overall improvement in their quality of life (Locker, 1998; Geertman et al., 1999; Heydecke et al., 2003; Quirynen et al., 2005; Emami et al., 2009; Harris et al., 2011).

Most studies of the outcomes of prosthodontic rehabilitation with implant overdentures have focused on the evaluation of clinical and technical aspects (Locker, 1998; Karabuda et al., 2008; Weinländer et al., 2010). Survival of implants, peri-implant hard-and soft-tissue parameters and post-insertion complications were the foci of interest of these studies (Payne et al., 2001b; Mericske-Stern et al., 2002; Walton et al., 2002; Attard & Zarb, 2004; Meijer et al., 2009; Mackie et al., 2011a,b). Other quantitative instruments such as the Oral Health Impact Profile (OHIP), and Likert or Visual analogue scales (VAS) have been devised to measure individuals’ subjective perception of their oral health and their satisfaction and quality of life respectively (Heydecke et al., 2003; Assunção et al., 2007; Hebling & Pereira, 2007; Souza et al., 2007).

Though critically important to establish the relative merits of different treatments with evidence from trials, such quantitative methods give one aspect of the clinical picture, with a limited representation of patients’ experiences and the impacts of such treatment on their life (Newton, 2000; Hyland et al., 2009). Furthermore, it is difficult to gain a deep insight into patients’ perspective from questionnaires or structured interviews that use predetermined response options. Qualitative research using semi-structured interview techniques can provide useful information regarding how patients view implant treatment, and may guide clinical practice and assist in refinement of therapeutic models of oral health (Newton, 2000).

Until recently, qualitative investigations of oral rehabilitation with implant overdentures were relatively scarce. Hyland et al. (2009) reported on patients’ perspectives of the effect of conventional and implant-supported overdentures on their enjoyment of eating. The main impact of edentulousness is the limitation of social participation and food choice, with significant improvement following rehabilitation with implant-supported overdentures. Apart from this study, no other qualitative studies of implant overdentures could be found in the literature.
The current investigation is part of an ongoing randomized controlled trial (RCT) comparing the clinical outcomes of titanium versus zirconia implants supporting maxillary and mandibular overdentures. The implants were placed using a novel distribution in both arches. In the maxilla, each participant received a mid-palatal implant and three anterior implants in the incisor and first premolar regions. In the mandible, three implants were placed: a mid-symphysis and bilateral distal implants in the first molar region. To the authors’ knowledge no previous studies used either zirconia or titanium implants in such a distribution to support overdentures. Clinical outcomes of this trial will be reported separately. The aim of this qualitative study was to gain a deeper understanding of patient perceptions concerning the novel aspects of this treatment.

**METHODS**

Participants were interviewed with respect to their perceptions and experiences of their implant-supported overdentures (Pope & Mays, 1995; Green & Britten, 1998; Stewart et al., 2008). The inductive, constant comparative method was used to analyze the data (Hallberg, 2006). This method aims at generating concepts, models or theories grounded in empirical data.

**Ethical Approval:**

Ethical approval for this study was granted by Regional Lower South Ethics Committee, New Zealand and written consent was obtained from all the subjects. The nature of the study was explained in detail to each participant. The participants were informed about the interview, its approximate duration, an overview of issues to be discussed and the fact that it would be audio-recorded. Confidentiality of the interviews was guaranteed. The participants were further reassured that their decision to participate in the interviews would not influence the treatment they receive in the clinical trial.

**Study design**

*Recruitment process*

Integrity sampling was employed where participants from the main randomized controlled trial constituted the population for the qualitative study. This allowed for selection of rich
information cases where a great deal about the issues of central importance to the research can be learnt (Patton, 2001).

Participants in the randomized controlled clinical trial had previously been recruited from patients attending the university clinic or referrals from dentists and denturists and randomly assigned to receive either titanium or zirconia implants to support their overdentures. For inclusion in the main study, participants had to be fully edentulous, medically and psychologically suitable for implant surgery, have sufficient alveolar bone for implants in the selected sites, and be able understand English or be accompanied by a responsible adult who could interpret. All the patients had their implant overdentures for at least six months prior to being interviewed.

Data collection

In-depth face-to-face, semi-structured interviews were conducted in the Prosthodontic Clinic at the School of Dentistry, University of Otago, New Zealand. Patients had received their overdenture treatment in this location and were familiar with the setting (Fitzpatrick & Boulton, 1994; Kitzinger, 1995; Burnard et al., 2008).

All the interviews were conducted by a single researcher who was not involved with the clinical aspect of the randomized controlled trial. This was done to ensure that the participants would frankly express their opinions without the fear that their responses would affect their treatment (Tong et al., 2007). An interview guide served as a basic checklist during the interview to ensure that all the relevant topics were covered. The same basic lines of enquiry were pursued with each person interviewed but participants were also encouraged to raise any other related issues (Patton, 2001; Stewart, 2008) (Table 6.1).

Data Analysis

The interviews were transcribed verbatim and analyzed using a thematic analysis inductive approach (Burnard et al., 2008). Two investigators read and independently coded transcripts using latent content analysis and constant comparison techniques to stimulate inter-rater reliability (McMillan, 2009). Initial coding labels were written in the margins of the transcripts to generate as many ideas as possible, which were used to finalize a list of coded categories. Relevant excerpts were then extracted and placed under each of those categories. Categories that were most prevalent were pursued throughout the entire data set to
develop central codes, a process known as focused coding (Pope et al., 2000). Analysis was continued until no new major information on the characteristics of each category was forthcoming. Definitions of the emerging codes and themes were written using typical examples from interviews to ensure clarity in communicating the meaning.

Methodological Rigour

Purposive sampling and multiple coding were employed to protect against bias, and enhance the reliability of the research (Stewart et al., 2008). Furthermore, to ensure the rigour of the study the data analysis was validated by a third party, a process known as peer debrief (Mays & Pope, 1995; Burnard et al., 2008).
### Table 6.1. Semi-Structured Interview Schedule

<table>
<thead>
<tr>
<th>Interview Guide</th>
<th></th>
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</thead>
<tbody>
<tr>
<td><strong>Key Question:</strong></td>
<td>What do you think about the implants you have now?</td>
</tr>
<tr>
<td><strong>Supplementary Questions:</strong></td>
<td>Patients’ perception of implant material (ceramic versus titanium)</td>
</tr>
</tbody>
</table>

**What do you think of the different implant materials?**

1. What factors would influence your choice of material and why?
2. Does implant material make any difference to you as long as your functional demands are met?
3. Have you heard of dental implants made of ceramic opposed to titanium? If yes where did you hear about it from?
4. Have you heard before about metal sensitivity? Does wearing any jewelry (watches, rings, earrings) causes you any sensitivity?

**Supplementary Questions: Patients’ perception of mid-palatal implant**

What do you think of where the implants were placed?

1. What were your feelings when you were first told about having an implant in the roof of your mouth?
2. Can you tell me about the impact, if any, of your implant dentures on your speech pattern particularly in relation to your top plates?

**Supplementary Questions: Patients’ perception of maxillary implant overdentures**

How do you feel about your new implant upper denture (plate) compared

1. Do you think it is better, worse, or the same? Can you explain?
2. Do you think it was worth going for implants in top jaw or implants in bottom jaw would have been sufficient?
3. Can you tell me how was it for you to get adapted to your implant dentures after receiving it?

**Supplementary Questions: Future choice**

1. Would you choose the exact same treatment again if you had the choice? Tell me about it.
2. Generally can you tell me if you felt any change in your self confidence since you received your implant dentures? Explain please.

### RESULTS

Sixteen participants (3 females and 13 males) completed the in-depth interviews after which no additional information was extracted, i.e. saturation was reached. The age of those interviewed ranged from 46 to 80 years (mean = 62.3 years). Eight subjects had titanium implants and eight had zirconia implants. Nine of the subjects were retired, two were farmers and one was on government support. The occupation of the remaining subjects ranged from part-time to full-time work.
Four major themes emerged from the data analysis and were grouped as follows: ‘perception of implant overdenture treatment’, ‘decisive factors in choosing implant therapy’, ‘factors influencing the selection of implant material’, and ‘perception of the mid-palatal implant’. Categories and subcategories were used to describe the properties and dimensions of each theme and are listed in Table 6.2.
Table 6.2: Four major themes, their categories and subcategories describing novel aspects of proposed overdenture treatment

<table>
<thead>
<tr>
<th>Major themes</th>
<th>Perception of implant overdenture</th>
<th>Decisive factor in choosing implant therapy</th>
<th>Factors influencing the selection of implant material</th>
<th>Perception of mid-palatal implant</th>
</tr>
</thead>
</table>
| Categories                                        | • Positive aspects of treatment**Subcategories:** 1. Improved eating patterns. 2. Improved social confidence. 3. Improved fit of dentures. 4. Negative aspects of treatment**Subcategories:** 1. Extensive surgical procedures. 2. Difficult denture manipulation. 3. Cleaning issues. | • Financial status of participants  
• Previous complete denture experience  
• Age of participants | • Metal sensitivity  
• Implant color  
• Strength and longevity of implant material | • Location of implant  
• Thickness of maxillary denture mid-palatal region and its impact on speech. |

**Perception of implant overdenture treatment**

**Positive aspects of treatment**

**Improved eating patterns**

All of the participants reported major improvement in eating, function and comfort with their implant overdentures, in contrast to their previous conventional denture treatment. Lack of fit and retention of their previous conventional dentures prevented them from eating the foods of their choice, particularly in social events. They refrained from hard-to-chew food such as steak, apples and nuts and preferred softer-consistency foods. Typical comments that highlight the improvement in their daily eating patterns were:

“I can eat my pineapple chunks now; they don’t shift all over the place. No, it’s just so convenient. They’re just like, probably having normal teeth back again. That’s what I find with them, you eat and they don’t jump up and down and get stuff stuck underneath them when you’re out at a restaurant.” (Participant 8)

“Well I, well before I was picking and choosing what I ate whereas now I sort of eat pretty much anything in the fridge..... I am pleased, I can eat anything.” (Participant 7)

**Improved social confidence**

Increased social confidence was one of the major advantages described by most of the participants. After receiving the implant overdentures, almost all the subjects felt that they regained their attractiveness and self-esteem. They were able to laugh and speak more confidently without the fear of losing their dentures. Patients considered implant-supported prostheses an integral part of their body that positively impacted their daily lives.

“You know you smile and you keep your mouth open and have a wee giggle, it feels good, it feels confident you know, yeah your teeth look nice. My wife thinks I look much nicer, it is for me important.” (Participant 4)

“Because your quality of life has just improved so much and your confidence goes up as well, you know if you feel confident in yourself you know you feel so much better.” (Participant 5)

**Improved fit of dentures**

The majority of patients who had a previous complete denture experience for a considerable amount of time indicated they always had significant difficulties wearing dentures. These problems were related to lack of dentures retention, which influenced their eating and social habits. Following treatment with implant overdentures the patients reported
that they no longer had problems with denture-induced oral ulcers, denture lifting while eating, or gagging caused by unretentive maxillary dentures. Typical comments were:

“I feel I just feel like they fit better, that they are just not moving around, I have got no rubbing or ulcers or anything because even with the glue and stuff they still move they still slip and by teatime I am trying to eat food and I couldn’t really because they were moving and then when they moved you get ulcers and sores and things but with these in, it is brilliant I don’t have to worry about it at all.”

(Participant 2)

“Yeah I can get uh; I can get them in now without gagging.” (Participant 10)

**Negative aspects of treatments**

**Extensive surgical procedure**

Three interviewees found the surgical procedure more traumatic than what they had expected.

“Oh well, the surgery was quite um; yeah I think possibly, it was a bit more dramatic than I thought. Yeah I think I didn’t quite realize exactly the amount of surgery that was involved, I just thought you know that they would make a small incision and plonk it in. I didn’t expect them to open, yeah I didn’t expect quite some major surgery and it was a wee bit of a shock.” (Participant 1)

**Difficulty manipulating the overdentures**

Though difficulty in removing the dentures could be considered as a drawback, it was also regarded as an advantage by the participants having snuggly fitted dentures:

“They are hard to take out but that is good because you don’t want them easy to take out otherwise they are not working, so they are good.” (Participant 3)

Some participants initially experienced difficulties in removing their maxillary dentures, while others found had problems getting both the maxillary and mandibular dentures out. With time, all of the participants managed to develop their own routine for easy manipulation of their overdentures:

“Yeah, I had a bit of trouble getting the top ones in at times. Yeah it is just a matter of getting the knack of popping them off, I don’t think they were that tight I just think it was the matter of learning how to manage and I know a few times I scratched my gums, but now it is not, yeah I don’t think much about it……..The bottom ones were relatively easier because I could get my thumb under there and then just seem to pop off more easily.” (Participant 1)

“Getting them out was shocking….I couldn’t get them out and I would panic and that of course made it worse……I would talk to myself don’t be stupid you can do
this and once I got it going it was fine, but I must admit in the beginning I did panic a bit because I felt I couldn’t get them out but I did get them out. But at the moment they are grand, yeah wonderful.” (Participant 4)

**Difficulty in cleaning implants**

Some participants found cleaning around the maxillary implants to be an issue, especially the mid-palatal implant. The difficulty was either due to lack of visibility and accessibility to the implant or the gagging sensation experienced during the cleaning procedures.

“Oh yeah, yeah no it is hard to see the top ones there but I give it a bit of swirl around.” (Participant 12)

“No, only difficulty is trying to clean it, it’s like sticking your finger down your throat, sometimes you feel gagging.” (Participant 7)

“Good as gold, only trouble, it is hard to clean I mean you can clean your teeth that is easy, you put them in Sterident and leave them and they clean them, but how do you clean the inside, yeah getting a toothbrush that starts bring tears to your eyes.” (Participant 3)

For two participants, cleaning around the implant was not the issue as much as sticking to a daily routine for cleaning around the implants.

“Um, difficult, I keep forgetting. Well I have never had a toothbrush in my mouth for nearly 40 years um, and my dentures the old dentures ah fitted so well that I would only take them out and I just put them back so I am sort of, even now occasionally now I will forget to take them out at night um, which I suppose is not what you are meant to do um, it is just a matter of trying to um, probably get a more of a routine.” (Participant 1)

**Decisive factors for choosing implant therapy**

The motivation to undergo implant treatment seems to have been a mix of factors involving financial status, the age of the participant and previous experience with complete dentures.

**Financial status of participants**

The interviews revealed that for most of the participants, implant therapy would not have been a possible option had not the cost been reduced as part of their participation in a clinical research trial. This was despite the fact that most of them were dissatisfied with their conventional dentures. Participants were of the opinion that the treatment was definitely worth the fees they would have incurred in the dental school (approximately NZ$15,000) if they had paid for it themselves.
“Yes, if I had the money I would never think twice about it. I would just get it done because I just think it’s been so good compared to what it was like before I had them…….. and I’d swear to everyone how successful I think it’s been for me.” (Participant 8)

In a follow-on question, interviewees were asked whether they would have opted for implant treatment if it had taken place in a private practice setting with a potential cost of up to NZ$50,000. Two of the participants strongly advocated the treatment regardless of the charges incurred: “yeah, wouldn’t worry, it wouldn’t worry me, I would be an advocate have it done to anybody……, it is worth the money and worth the confidence that it gives you” (Participant 5). The rest of participants hesitated and replied with quotes such as:

“I do not know, I just do not know what I’ll do, not knowing what I would get, I go to buy a car I look at it, I know what I am getting and that’s the end product, with this I do not know what I am getting, I have got nothing to compare it with, with money being no object I still want to know what I am getting.” (Participant 7);

“If someone said to me it would be $20,000-$25,000 I would say yeah that would be alright but if it goes higher than that I wouldn’t pay that much of money, and not for the reason I couldn’t afford it I think but there comes a time when buying a car you know you can buy a car for $30,000 dollars….. For myself I probably would not do it, but my wife if she needed the same thing I would let her do it to look nicer, I just couldn’t care less.” (Participant 4)

**Previous experience with complete dentures**

In light of their experience of implant overdenture treatment in both jaws, participants were asked whether they would still undergo the same treatment or whether they would limit treatment to one particular jaw. Replies varied based on previous negative experiences with conventional complete dentures, particularly fit and retention. Participants who managed well with their maxillary dentures but had trouble with their mandibular dentures opted for implant therapy in the mandible alone. Typical quotes were:

“Well I definitely wouldn’t bother doing the top again, the result on the bottom is quite good in the fact that they don’t lift with your tongue, the top before stayed well with the suction……..if I had the choice I would probably just say the bottom, um because it was the bottom ones that were unstable.” (Participant 1)

Participants who had difficulties wearing their maxillary denture preferred having implants in the maxilla. Typical quotes were:
“I take the top, yeah because, the top ones were always falling out before, the bottom teeth, they stayed in on the mouth. ...... but the top ones I couldn’t wear, I had to put that much glue on them to keep them in, well it wasn’t even funny but the bottom ones stayed reasonable.” (Participant 7)

Others who had trouble with both dentures or thought that one could not work without the other preferred to have implants in both jaws. An example of comments:

“If I could afford I would probably get the whole lot done, not just one. Because I don’t think one would work without the other. I think if you got one, I have never had the experience but I could think about it, if you got one solid in your mouth and one flopping around, one is going to work, and the other isn’t” (Participant 3).

Those patients who entered the clinical research trial with some remaining natural teeth (prior to extractions and implant treatment) or who had been wearing their complete conventional dentures for only a short period prior to implant treatment, based their selection on aesthetics and comfort perspectives:

“For me personally, if a person smiles you will always see the top ones not the bottom so it is better, my way of thinking, to have nice top ones than bottom ones,......... I think the ones that hurt the most would go and I would replace that if they were sore. I would say take them out.....if everything was sore I think you should have both done.” (Participant 4)

Age of the participants

Age emerged as one of the factors that could be influential when deciding on the implant therapy either in the dental school or privately.

“Yes, if I was say in 50s no problem, or the 40s, I mean people have dentures when they are 40 don’t they. No problem, it is the best thing you could do, wouldn’t you say. It does not matter if you only have them for ten years, it is still worth it when you are younger.” (Participant 6)

“I mean I am going to have these forever, I am going to have dentures, I am not going to be growing any new teeth so I have to have dentures and, I mean like if I was 60 I probably wouldn’t spend the money but being 40, it is another 40 years so you know I might as well, whereas if I was older I probably wouldn’t have done it.” (Participant 2)

Length of treatment

Despite the relatively long-time frame associated with the treatment, most of the participants did not consider this to be crucial when deciding on implant therapy.
Furthermore, they found that the treatment outcome and its impact on their daily lives outweighed the time and the effort required:

“That did not bother me, even if I was working it wouldn’t make any difference cause I had a job I could fit it in with.” (Participant 7)

“Yeah I think it could take a couple of years, in my way of thinking it is ah, it is technology that people learn of to pass it on and to study and to go back, time involved was not important to me.” (Participant 4)

Some of the participants suggested that an approximate time line of the overall treatment defined at the initial diagnostic stage would be more helpful during their decision making.

“When I first started I didn’t have in my head I think a clear time line of how long it was going to take, ok, so possibly one of the first things you give in the, initial information is possibly like a time line guide.” (Participant 2)

Extended overall treatment time negatively influenced the opinion of two participants regarding the whole procedure and their subsequent future recommendation. Increased treatment time resulted from the failure of some implants and their replacement. This was further complicated by the long travelling distance for some participants, rising fuel prices and the lack of any travel allowances provided by government to cover any sort of dental treatment:

“No I wouldn’t recommend it to other people, yeah, just how long it all took, like I did a lot of travelling to come and everything, I don’t know you know it would have to be up to that person.” (Participant 12)

“you know if you lived in the city, or handy to city, it would be no hassle, but when you live an hour and a half away and run a vehicle today, you know it is not cheap to run a vehicle, fuel has gone up, I think I would probably, for that reason alone I think I would decline. It is tough when you are a pensioner.” (Participant 13)

A number of comments were made expressing dissatisfaction with the lack of any governmental support to cover dental services, compared to medical treatment:

“My daughter has got hepatitis C, she comes to Dunedin for treatment and it is pretty tough but she gets travel assistance, she had to stay overnight, she gets accommodation allowance, yeah, and you know it covers it and that is the thing so, but I don’t know I suppose the health donor can’t go that far and I don’t think we will change them will we..... even some assistance would have been good especially for out of town people.” (Participant 13)
In the same context, other subjects thought that all health services, both medical and dental, should be provided free of charge or at least partially covered by the government:

“I do not think you have to pay for any medical cost but it is a political issue……we could debate about it whole day …….but it would be nice if it was all covered.” (Participant 14)

Decisive factors for selecting implant material

Despite the fact that this was a randomized controlled trial where participants were allocated to receive one of two implants, they were hypothetically asked about different factors they might consider when deciding on implant material. The major decisive factor for most of them was the strength and longevity of the material.

Metal sensitivity

Prior to reading the information sheet, most of the participants revealed no prior knowledge of the different materials used in fabricating dental implants. During the interviews, most of the participants, except two, did not know what metal sensitivity was. However, when asked whether they were aware of any family members who could not wear specific type of jewelry because of a rash or allergic response, some of the interviewees gave positive replies:

“Yes I have a daughter that has allergy to metals, ah and has to be very careful what she wears because she comes out in big rashes and, a buckle and yeah, so I just assumed that this was the main reason, is that some people will have allergies to metals and so ceramic rather than titanium.” (Participant 1)

Implant color

The fact that the implants were completely covered with the dentures and could not be seen was the main reason why the implant color was not considered when deciding on implant material. The color of teeth and denture flanges representing gingival tissues was more important to the patients than the implant color from an aesthetic point of view.

“No, I don’t think it would make a difference to me particularly because they are both covered 99% of time so it wouldn’t make a difference.” (Participant 2)
**Strength and longevity**

Strength and longevity of the implant material and their impact on post-insertion maintenance requirements were the main factors raised by the participants:

“*As long as they work properly and they last a long time, that’s all what I care for.*” (Participant 15)

“*The important factor is they’ve both got the same strength and lasting power.*” (Participant 9)

Different patterns were detected when the participants were asked about their material of preference if they had a choice. Seven participants showed a tendency towards favoring titanium implants. This was based on the predetermined belief that titanium as metal exhibits greater strength than zirconia:

“*Well in my mind titanium would probably be stronger than ceramic. Well one is metal and the other one is pottery or something like that isn’t it. But I am probably wrong, or they wouldn’t be using it, I know ceramic washers in tapes but I don’t know about implants with them.*” (Participant 5)

“*It is more reassuring thinking that it is titanium rather than ceramic something that you know, I have got ceramic pieces at home on my mantelpiece, I just yeah I don’t know, it is more reassuring thinking that they are metal. If I had the choice I’d probably go titanium.*” (Participant 2)

Five participants revealed no preference towards either of the two materials, stating that they had no background knowledge about the materials and would defer to expert opinion or others with similar prior experience:

“*I don’t know, I wouldn’t, I would have to go to the experts and the surgeons or the staff and ask them what would they prefer.*” (Participant 9)

“*I suppose I would have to speak to someone else how they are coping with them, yeah I don’t really know because if you haven’t tried them you don’t really know.*” (Participant 13)

The rest of participants preferred to have ceramic rather than titanium implants, considering it to be healthier, more natural and closer to bone in qualities. Quotes showing this were:

“*I don’t know, it doesn’t seem natural to put titanium in your mouth.....I guess because you are just used to your teeth being white, I am just glad I got ceramic, I was really chuffed with that but um, yeah I suppose titanium is not that good for you anyway.*” (Participant 11)
“I would’ve probably chosen ceramic…… more superior, closer to bone and benefit to your body and with design better to your body.” (Participant 14)

Participants’ perception of mid-palatal implant

**Location of the implant**

Contrary to what was expected, all participants except two did not mind having an implant in the middle of their hard palate. Typical comments were:

“It takes a bit of getting used to all, but I suppose where they are or what they are um, you got to get used to one you get used to them all, I didn’t, I haven’t found that any one in particular is any different from the other. (Participant 1)

“No I knew that beforehand about the roof, I didn’t give it a thought actually just an implant to me.” (Participant 4)

The participants who were initially concerned about the mid-palatal location commented:

“Ah, at first I was not very keen in my mind on the one in roof of my mouth, because it is not the jaw, but after all that ends, it doesn’t feel anything I don’t mind anymore.” (Participant 6)

**Thickness of maxillary denture mid-palatal region and its impact on speech**

All participants except three found no change in their speech pattern or noticed any difference in the thickness of the mid-palatal region of their maxillary overdentures compared to the conventional counterpart. Furthermore, some of them found the thickness of mid-palatal region to their overdentures to be less compared to their old dentures

“Oh, it is normal. My last one was thicker but this one is thin, my last one because it broke into half so he made me a thicker one but this one is thin like my first one thin one.” (Participant 6)

The participant who noticed an increase in the thickness of mid-palatal region found it quite easy to adapt to with no effect on speech: “It may have been increased but you sort of got used to it as you progress through the whole operation,” and when asked about speech replied, "no, perfect, nothing ever changed” (Participant 3).

Both of the participants who experienced alteration in their speech patterns attributed this to not wearing either mandibular or both maxillary and mandibular dentures before and their need for time to adapt.
“Yeah, I think for quite some time I was sort of whistling every now and then, yeah I just don’t know why but as I say I have worn top dentures for years and not having worn bottom ones for nearly 40 years, yeah might take a longer to get used to, I sort of notice the bottom ones more than I notice the top ones.” (Participant 1)

“I was like a flaming idiot for the first two or three days. But I persevered and in time it came better and better and better. So now, I’m quite confident, no trouble at all. But it’s just like everything else, you get something and you persevere with it and try and try until it comes right.” (Participant 7)

DISCUSSION

The purpose of this qualitative study was to assess the patient-centered perceptions of a novel implant overdenture treatment protocol. Our key findings related to the patients' satisfaction and perceived cost as well as positive and negative aspects of the proposed treatment along with considerations regarding implant materials and sites. The novel implant protocol was acceptable to patients.

Discomfort caused by conventional dentures was widely reported by all of participants. This is unsurprising, since our study population consisted of denture-wearers who had previously volunteered for a randomized controlled trial that included implant treatment to remedy unstable conventional dentures. The reported problems included denture looseness, sore spots, chewing difficulty and food impaction underneath the dentures, all of which improved upon wearing implant overdentures. Not only was denture function improved, but those interviewed also felt that their self-image and social self-confidence was also enhanced. Other groups have also reported that implant overdentures improved patient satisfaction and oral health-related quality of life when compared with conventional dentures (Boerrigter et al., 1995a,b; Meijer et al., 1999; Awad et al., 2000, 2003a,b; Doundoulakis et al., 2003). Participants who wore implant overdentures found it easier to chew, had greater denture stability and comfort and reported an improved self-image (Cibirka et al., 1997; Allen et al., 1999; Harris et al., 2011). Rates of patient satisfaction with chewing, stability and comfort provided by implant overdentures were 97% after 10 years of function (Quirynen et al., 2005). The degree of patient satisfaction appears to be correlated to enhanced masticatory function, comfort, esthetics and self-image. Cibirka et al. (1997) suggested that dental implant therapy might reduce patient anxiety related to conventional prostheses thus modifying their personal and psychosocial behavior. It is worth noting that all of these studies focused on mandibular implant overdentures opposing a conventional maxillary denture. It is clear from our results
that for some patients, their preference for single versus two-arch treatment would be determined by whether they had previously experienced problems with their mandibular or maxillary prosthesis, whilst other patients would be content to leave this decision to the expert clinician.

In agreement with several other studies, cost was found to be a high priority consideration in the choice of prosthetic rehabilitation (Palmqvist et al., 1991; Tepper et al., 2003; Zitzmann et al., 2006). The majority of the participants in the current study would not have sought implant treatment had it not been provided for a very low nominal fee as part of a research trial. Similarly, a Swedish study found cost to be the most common cited reason for declining implant treatment among those who reported a possible treatment need (Narby et al., 2008). When Pommer et al. (2011) assessed patients’ perceptions of implant therapy among 1000 adults in the Austrian population, half the group were convinced that dental implants were only for the rich and rated cost as the major disadvantage of implant dentistry. A survey evaluating the knowledge and attitude of elderly persons towards dental implants revealed that cost was the predominant reason for hypothetical objections towards implant treatment (Müller et al., 2012). Nevertheless, the majority of the interviewees in our study considered the cost of implant treatment justified by the improvement that the treatment brought to their lives. This is in agreement with the findings of Johannsen et al. (2012) where the majority of patients they interviewed considered the treatment expensive but worthwhile. The participants in our study further recommended that if the payment was to be allowed in installments, this would make it more accessible for a larger sector of population. Esfandiar et al. (2009) has also reported an increase in patients’ willingness to pay for implant treatment if payment was permitted on a monthly installment basis.

All the participants were willing to pay up to NZD $30,000 for implant overdenture treatment. When the amount was doubled, all of the subjects but two considered this too expensive. Others have reported that the amount that patients are willing to pay for implant treatment is approximately half that of the market price (Leung & McGrath, 2010). They suggested that a study population drawn from a University Dental Hospital might expect to be offered treatment at a much lower fee than the market rate. The authors recommended further studies to support or refute this. Our study suggests another dimension to this response. Our interviewees were not willing to pay such a high value for what they called an “unknown product” without an opportunity to trial the product as they might do with other major purchases. Our interview approach measured incremental increases in hypothetical cost
against willingness to pay. This allowed us to assess patient perceptions of the cost-benefit ratio of the treatment.

Most dental treatment for adult patients in New Zealand is paid directly by the consumer; third party insurance support is rare, apart from a national scheme for treatment of accidental injuries. Some participants found it unjustified that pensioners and those with health issues should pay any sum for dental treatment, having worked all their lives and now being on limited income. Their thoughts were that Government should implement programs to assist elders with dental treatment including implant overdenture therapy. A Canadian study assessing patient perceptions of the role health care plans should play in financing dental prosthetic treatment reported similar results. In this paper, 41% of the subjects believed that the cost should be split with Government based on individual income; 28% thought that a 50/50 split was justified and the rest suggested a range from 60/40 to 99/1 (Esfandiar et al., 2009). Similarly, in an Austrian study three-quarters of participants interviewed thought that the social security agencies or sick fund should pay for the implant treatment (Pommer et al., 2011).

We found that socio-demographic factors such as gender and age further influenced willingness of patients to pay for implant therapy. Young age (≤ 55 years) seemed to positively affect the decision of opting for implant therapy. On the other hand, with increasing frailty possibly other issues may take priority and dampen the concerns about the personal appearance and social interactions (Müller et al., 1994; Heydecke et al., 2003; Donnelly & MacEntee, 2012). It has been suggested that when considering time, effort and money invested on such a sophisticated dental treatment, elderly people may not find it worthwhile relative to their remaining life expectancy (Müller et al., 2012). Thus despite the fact that there is no scientific evidence supporting age as a contraindication for implant treatment from a clinical and technical point of view (de Baat, 2000; Bryant & Zarb, 2002; Lee et al., 2010), it might be from a patients’ perspective. Müller et al. (1994) found that expectations and demand for prosthetic care decline with age. Older people prefer to accept functional impairment rather than cope with the potential changes in appearance, function or shape that can occur with new dentures. Another study evaluating patient-perceived cost, patient satisfaction and implant acceptance found that the implants would be accepted by 73% of those below 30 years of age, by 64% of those ≤ 50 years and by no more than 51% of those > 50 years (Tepper et al., 2003). This highlights the importance of evaluating psychological
aspects and understanding the patients’ expectations prior to the initiation of treatment for optimal outcomes (Roumanas, 2009).

Some of the statements we recorded suggest that gender may play a role when deciding on implant treatment. Only female participants were willing to pay for the treatment at the higher “private practice” cost. The reasons they gave mainly related to the increased confidence the implant prostheses had imparted to their social life. One participant was willing to pay full fees for implant therapy for his wife if she needed this treatment, but not for himself. Gender variations in oral health and in accessing oral health services have long been documented (Lo et al., 2001; Tamaki et al., 2004; Leung & McGrath, 2010). McGarth & Bedi (2000) found that gender differences play a role in the social impact of oral health upon perceived quality of life. Poor oral health has a greater impact on quality of life in women than in men. Another study investigating the impact of edentulousness and oral rehabilitation found that women were more concerned with the impact of oral health on their attractiveness, whereas men were more functionally-oriented, stressing the importance of being able to eat and chew (Trulsson et al., 2002). However, our findings should be accepted with some caution due to the small number of female participants.

We found that previous experience with conventional dentures plays an important role when deciding on implant treatment. Allen et al. (2006) and Emami et al. (2009) concluded that the benefits of implant therapy to different group of edentulous patients vary as patients differ with regard to their denture histories, functional or anatomical deficiencies and their expectation of treatment. Participants who were satisfied with their previous maxillary dentures were unlikely to undergo implant therapy again in the maxilla. In this respect, de Albuquerque et al. (2000) found similar patient satisfaction when comparing maxillary conventional to implant overdentures and suggested that the latter should not be considered as a treatment of choice in patients who have good bony support for their maxillary conventional dentures. A longitudinal clinical trial undertaken by Allen & McMillan (2003) to compare the impact of oral implants on the psychosocial well-being of subjects with problems related to their conventional dentures suggested that receiving implants in only one jaw might not satisfy some patients. Similarly, in our study some of the participants considered it impractical to have implants in one jaw and not in the other.

Anxiety related to surgical aspect of implant treatment has been noted in other studies (Kiyak et al., 1990; Walton & MacEntee, 2005; Schwartz-Arad et al., 2007; Müller et al.,
A study by Walton & MacEntee (2005) found that 36% of participants refused an offer of free implants because of concerns regarding the surgical risk. Another study investigating the influence of anxiety on the experience of pain at implant insertion found that this correlated to patient anxiety levels which were highest immediately prior to the surgery (Eli et al., 2003). We found a gap between participant expectation of pain during surgery and their actual experience. For future trials we intend to minimize anxiety prior to surgery by detailed explanation of the surgical procedure, using illustrative videos, photos, models and possibly discussion with other patients who has gone through the same experience. Similarly, a Swedish report recommended condensing patient experiences into an information leaflet and making it available to prospective implant patients (Sandberg et al., 1999). Some participants even suggested that dedicated websites for participants to log onto prior to surgery might prove helpful.

The initial difficulty in manipulating the overdentures reported by some participants highlights the importance of pre-operative evaluation of manual dexterity and adaptive capabilities during the diagnostic and planning phase of treatment. Hypothetically, such a difficulty would have been expected with the mandibular overdentures as these had larger attachment systems and consequently increased retention, but this was not always the case; some participants reported difficulties with their maxillary overdentures or with both dentures. This suggests that patient adaptation and manual dexterity play more of a role than the amount of retention imparted by the attachment system. Over time, all of the participants adapted until they had no difficulty manipulating their overdentures, supporting our contention that dexterity plays a greater role than the type of attachment. In a similar context, a patient cohort with spark erosion overdentures found initial difficulty mastering the swivel lock retentive element at the delivery appointment. However, at the one-week recall appointment the majority of subjects demonstrated their ability to manage the attachment system, highlighting the importance of patient adaptation and dexterity (Toljanic et al., 1997). Another clinical report recommended that dexterity should be considered during the design phase, to allow easy insertion and removal as well as proper oral and denture hygiene measures, particularly for functionally impaired patients (Al-Amri, 2008).

The increased fit and retention of implant-supported overdentures can be considered an ideal compromise for those subjects who desire a fixed restoration but cannot access this treatment due to limited financial resources or anatomical considerations. This is particularly relevant when rehabilitating the mandibular ridge, where retention and fit of dentures is an
issue of constant concern. An interesting topic for future research would be to compare patients’ oral function and satisfaction between three different modalities; the proposed novel mandibular 3-implant protocol, implant overdentures on two interforaminal implants, and fixed implant prostheses.

The importance of good access for cleaning the implants cannot be overemphasized. In the present study one-quarter of interviewees reported that they found it difficult to clean around the mid-palatal implant. However, clinically no plaque was detected around these implants, possibly due the mucosal biotype in the mid-palatal region which is taut and firmly attached to the underlying bone (Squier & Brogden, 2011). Thus, despite the difficult accessibility of the mid-palatal implant, mucosal type combined with the oral hygiene measures practiced by the participants may prove to be satisfactory. The findings that some participants found it difficult to develop a daily routine to clean their dentures supports the view that the pattern of preventive oral habits established in younger years continues into old age (MacEntee et al., 1993). Similarly, in the study by Johannsen et al. (2012), the majority of the patients perceived the oral hygiene procedures to be too much time consuming. This stresses the importance of developing a maintenance oral hygiene program when planning implant prostheses for edentulous patients.

Our novel design included a mid-palatal implant which was a potential issue for prosthodontics reconstruction. Increased thickness of palatal vault would be expected to adversely affect patient phonetics and may also be unpleasant once the denture was removed. However, all participants but two reported no change in their speech pattern nor did they find it awkward to have an implant in such a location. This can be explained on the basis of patient’s adaptive increase in the interocclusal distance in both vertical and antero-posterior directions when the thickness of the palatal plates is increased (Schierano et al., 2001; Zhang et al., 2009). Oro-sensory feedback would provoke a more posterior positioning of the tongue, causing as in the case of macroglossia, a narrowing of the pharyngo-tracheal diameter forcing the patient to increase the size of his mouth opening (Schierano et al., 2001). Mays & Stone (2011) suggested a compensatory oral motor function when palatal contour is altered to achieve acoustically and perceptually successful speech. A previous case report of a subject rehabilitated with maxillary three-implant overdenture (two crestal and one mid-palatal implant) showed complete patient satisfaction with all the aspects of treatment at the 1-year follow-up (Machado et al., 2008).
Our interviews found that the knowledge of the participants regarding the oral implants and different materials used for their fabrication was limited. This has been noted in previous studies. In the survey by Müller et al. (2012), 28% of participants showed complete lack of knowledge of oral implants. Furthermore, one-fifth of those who heard about implants beforehand were not able to describe their understanding of oral implants. When asked what materials are used to fabricate oral implants, most assumed some kind of metal without specifying type, but some suggestions included silver, porcelain, steel, gold, acrylic, plastic; only 1% suggested titanium. Potential explanations for the limited knowledge about oral implants include a lack of interest regarding treatment options that they could not afford, or receiving insufficient information from their dentists. A different scenario might be observed among patients attending private practice.

The belief of some participants that ceramic is more natural and closer in properties to bone than titanium is in accordance with the popularity of the “metal-free-dentistry” concept within parts of society. Whether metal sensitivity and titanium allergy is a real factor or not in implant failures (Siddiqi et al., 2011; Javed et al., 2013), a need will always exist for alternatives to titanium such as ceramic implants. However, the prevailing concept that ceramics is much weaker than titanium and more liable to fracture should be appropriately addressed. This can be achieved via extensive laboratory testing and in-vivo animal studies to enhance confidence in this material and enable the production of a body of scientific evidence to match that available for titanium implants.

Nice teeth and a nice smile are a part of the quest for eternal youth (Brondani et al., 2007). Our interviewees were less concerned about the colour of the implants and mostly focused on the shape and colour of the denture teeth and flanges. The implants were covered by the dentures most of the time and could not be seen. We suggest that when replacing missing teeth in aesthetic areas, implant colour may be more influential when deciding on implant material (Belser et al., 2004). Thus, for overdenture patients implant colour was not as critical as the physical properties of material and its implication on future maintenance requirements.

Our methodology met the criteria for rigorous qualitative research. Intensity sampling allowed for selection of rich information cases from which we learnt a great deal about the novel treatment. A thematic inductive approach was used to categorize the data, and the literature was used to confirm the analytical categories. Multiple coding and peer debrief were followed to stimulate inter-rater reliability and address bias concerns. We have described our
methods in detail and would encourage other research groups to investigate the responses of edentulous patients from other ethnic, racial and socio-economic domains and after treatment using protocols that differ from ours. The generalizability of our findings should be approached with some caution as these may be specific to the context and experiences of our study population. We believe that the information generated by our study is valid for other cohorts of edentulous patients attending our institution and possibly for patients seeking implant overdentures within University dental clinics in other nations. Knowing how our patients think, what drives their decision towards implant treatment and what factors may improved their satisfaction with treatment outcomes, will in the future guide discussions between clinicians and patients who are considering this treatment.

CONCLUSIONS

Implant treatment greatly improves the oral function and psychosocial aspects of edentulous patients and this is positively reflected in their quality of life. Cost represents the main barrier that prevents patients from seeking implant treatment; mitigation of this through payment schemes, insurance or other third-party payment may increase acceptance of oral implants. The knowledge of edentulous patients regarding dental implants and different implant materials is limited and should be enhanced. The mid-palatal implant site may be a potential alternative to extensive surgical procedures during the prosthodontic implant rehabilitation of atrophic maxillary ridges. Our novel mandibular design offers patients the advantages of a removable prosthesis with increased retention. Finally, our results strongly support the utility of qualitative analysis of patient-centered outcomes when examining new treatment protocols and materials.
CHAPTER VII

General Discussion, Conclusions, and Directions for Future Research
GENERAL DISCUSSION

Removable implant overdentures have become a widely accepted and a well-established treatment modality for the management of edentulous patients. Commercially pure titanium (Cp-Ti) and its alloys, as biomaterials of choice, are the most commonly used materials for the fabrication of oral implants due to their suitable mechanical properties and biocompatibility, and are expected to remain so in the long-term future. However, controversial reports about possible allergic reactions to titanium have propelled the search for an alternative implant material.

Ceramic materials are amongst the most popular materials of those proposed as a potential alternative to titanium, particularly yttrium-stabilized tetragonal polycrystalline zirconia (Y-TZP). Zirconia exhibits good physical and mechanical properties. Stress induced transformation toughening is a unique characteristic of Y-TZP as it undergoes a phase transformation process, a process that results in local volume expansion and therefore counteracts crack propagation.

Preclinical studies, case reports and randomized controlled trials on zirconia implants for the rehabilitation of partially dentate patients, as mentioned in the Literature Review (Chapter 1), have revealed favourable outcomes, albeit in the short-term. However, there is a lack of published literature on the use of zirconia implants to support overdentures. This may disadvantage a group of fully edentulous patients who request or prefer a metal-free prostodontic rehabilitation or exhibit metal allergy. Thus, a randomized clinical trial was designed to evaluate and compare the clinical and prostodontic outcomes of similar design zirconia and titanium implants used for overdentures support.

Traditional implant distribution customarily used with titanium implants for support of maxillary and mandibular overdentures may not prove ideal, given the brittle nature of zirconia implants and the need to minimize future prostodontic maintenance requirements. Thus this thesis proposed novel implant distributions for the support of maxillary and mandibular overdentures using one-piece zirconia implants. The implant distributions were as presented in Chapter II and III: in the maxilla, a mid-palatal implant and three anterior implants in the incisor and first premolar regions or a mid-palatal implant, an incisive canal implant and two anterior implants in the premolar region; in the mandible, a mid-symphysisal implant and bilateral distal implants in the first molar region. The rationale of such layout
designs evolved from a critical review of biomechanical principles of removable partial denture prosthodontics and its close similarity to the situation created by implant-supported overdentures. It was proposed that biomechanically the novel implant distributions would allow for an optimal load distribution, and thus preserve the integrity of zirconia implants. The prosthodontic perspectives of the suggested novel designs focused on improving the determinants of prosthodontic success, the retention and stability of overdentures, congruent with reduced prosthodontic maintenance and improved biological outcomes. Thus, a series of *in-vitro* (Chapter II) and clinical *in-vivo* (Chapter III) investigations were subsequently established prior to the commencement of the randomized clinical trial and prior to recommending this approach for a wider application.

In Chapter II, part 1, the biomechanical behavior of zirconia and titanium implants was assessed and compared using numerical modeling (FE analysis). Comparable stress and strain values were found in the peri-implant bone for both types of implants. Maximum tensile stresses that developed within both implant materials were well below their fracture strength. All calculated maximum strain values within the bone adjacent to the implants on the loaded side were within the remodeling strain range of bone. These findings suggested that from a biomechanical point of view, ceramic implants made from yttrium-stabilized tetragonal polycrystalline (Y-TZP) zirconia may be a potential alternative to conventional titanium implants for the support of overdentures.

Based on the outcomes of the first part of Chapter II and with the aim of optimizing the mechanical integrity of zirconia implants, a further FE analysis (Chapter II, part 2) was performed to compare the biomechanics of the novel proposed implant placements with that of conventional maxillary overdenture support. The novel designs involved either a mid-palatal implant, bilateral premolar implants and one off-center crestal implant (D2, see Fig 2.10 b) or a mid-palatal implant, an incisive canal and bilateral premolar implants (D3, see Fig 2.10 c). The novel designs (D2 and D3) were found to have a comparable biomechanical behavior to that of the conventional design (D1). However, in D2 and D3 the mid-palatal and incisive canal implants were found to have a substantial load-bearing role, particularly under oblique load. As shown in Chapter II in Fig 2.12 b, 2.14 and 2.15, most of the load with the D2 was being shared between the mid-palatal and the most distal implant on the loaded side. Of particular interest in the case of D3 was the shift of maximum principle tensile stress on the implants to the wide trans-mucosal collar of the incisive canal implant further from the vulnerable neck region of the implant (Fig 2.16 and 2.17). Denture displacement values were
lower in D2 and D3 compared to D1. This decreased denture movement suggested potential reduced sliding contact of the attachment systems against the ball abutments, implying minimal maintenance requirements and improved patient satisfaction.

A pilot study (Chapter III) was performed prior to the outset of the actual clinical trial to evaluate the prosthetic perspectives of the proposed novel designs. Four participants were included and each received four maxillary and three mandibular one-piece zirconia implants. The implant distribution was: in the maxilla, a mid-palatal implant, an incisive canal implant and two bilateral implants in the first premolar region; in the mandible, a mid-symphysis implant and bilateral distal implants in the first molar region. The outcome of this study showed that the incisive foramen can be used as an alternative implant site for the rehabilitation of the atrophic edentulous maxilla. The use of this site did not cause any discomfort or sensory disorder for the participants, nor was there any detectable alteration in their speech pattern. At the one-year follow-up, all the implants were stable and osseointegrated at the time of pick-up of attachments except for one implant, which was loose and consequently removed. Of greater concern was the need for the excision of hyperplastic peri-implant mucosa, particularly around the incisive canal implant, to expose the ball abutment of the one-piece zirconia implants. This was attributed to design features of the prototype zirconia implants rather than the prosthetic protocol. Accordingly, a modified quadrilateral design where the incisive foramen site is replaced by an off-centered anterior crestal implant was proposed. This design would retain the favorable biomechanical distribution of forces seen in the initial design.

The major outcome of this thesis (Chapter IV) reported on a randomized clinical trial that further evaluated and compared the clinical and prosthetic outcomes of similar design continuum and zirconia implants (Y-TZP) used for the maxillary and mandibular overdentures support. This study opted for a conventional loading protocol, allowing for a 12-week healing period before the pick-up of attachments. However, since our study employed single-piece implants placed using a one-stage surgical approach, the possibility that indirect loading of the implants occurred prior to fitting the definitive prosthesis cannot be discounted (Tawse-Smith et al., 2001; Prithviraj et al., 2012).

As outlined in Chapter IV, the peri-implant marginal bone levels during the first year did differ between titanium and zirconia implants. Although this difference was statistically significant (P< 0.05) the minor difference in bone loss between the two groups might not be
clinically relevant. The mean MBL for titanium and zirconia implants was 0.18 and 0.42 mm respectively. The difference in the surface roughness between the two implant materials is suggested to partly account for this. The results of experimental research in animal models concur with the previous suggestion. Surface modified zirconia implants resulted in greater bone response and higher torque removal values than machined surface zirconia implants (Gahlert et al., 2009). In the current study, minimally rough surface zirconia implants with R_a values ranging between 0.5-0.8µm were used as opposed to moderately rough surface (Ra 1-2µm) titanium implants (Albrektsson & Wennerberg 2004a). However, it remains to be determined, by strong supportive evidence from randomized clinical trials, whether different implant surface treatments bear any significant relevance in long-term implant outcomes. Another possible reason for the increased bone loss around zirconia implants could be the difference in the modulus of elasticity between the two implant materials. The elastic modulus of zirconia is almost double that of titanium, which may have modified the response of peri-implant crestal bone, though this was not clinically significant as evidenced by comparable survival rates between the two groups. The overall low success rate observed for titanium (57.1%) and zirconia (57.5%) implants was largely related to implant failures in the maxilla. Furthermore, the outcome of mid-palatal implants was relegated to the survival category due to difficulty in acquiring radiographic images of these implants.

In agreement with previous studies, the present investigation found a higher failure rate for both types of implants in the maxilla compared to the mandible (P<0.05). Similarly, the prediction model for implant failures revealed a higher risk of failure for implants placed in the maxilla. The survival rate was 95.8% and 90.9% for the mandibular titanium and zirconia implants respectively. The corresponding values for the maxillary implants were 71.9% and 55% respectively. This may partly be explained by the difference in bone quality between the two edentulous arches (Bryant, 1998; Esposito et al., 1998b). Generally, the mandible has a denser and thicker cortical and trabecular bone component than maxilla (Bryant, 1998; Esposito et al., 1998b). The presence of dense bone in the mandible may favor early implant stabilization, which is one of the prerequisites for predictable osseointegration (Truhlar et al., 1997). Therefore, accurate diagnosis and treatment planning is of the utmost importance for optimizing treatment outcome, and this is particularly relevant in the maxilla. Accurate diagnosis and treatment planning should include the use of implant systems with well-established surface characteristics, selection of optimal implant recipient sites with adequate bone quantity and quality and the use of conventional loading protocol to enhance the process of osseointegration.
At the commencement of this study in 2009, the additional usage of posterior mandibular implants combined with a single mid-symphysseal implant was rare. However, the high success rate observed in the current study for the posterior mandibular implants supports the predictable use of short and wide diameter implants. The positioning of two posterior implants combined with a single mid-symphysseal implant creates a completely implant-supported overdenture rather than the more common approach of implant-and-mucosa supported overdenture. The posterior implants create a Kennedy III-type situation, as opposed to a distal extension Kennedy I-type situation (Feine et al., 2002; Carr et al., 2005). This tripod design is expected to reduce posterior bone resorption as compared to the commonly used 2 to 4 inter-foraminal implant overdenture design (Osman et al., In Press-a). This is particularly relevant for younger individuals with the need of mandibular overdentures where posterior bone resorption may be an issue with the 2-interforaminal overdenture design. However, this contention must be proven by well-designed randomized controlled trials.

A distinct feature of the current study was the high failure rate of 42.1% observed for mid-palatal implants (Chapter IV). The vast majority of failures (5/8, 62.5%) occurred during the early healing phase. This is in accord with previous published studies that have reported on the outcomes of mid-palatal implants (Asscherickx et al., 2010; Jung et al. 2011). The most incriminating factors for the observed failures seem to be a mixture of clinical handling procedures. These include the learning curve of the surgeons related to the placement of the relative short length implants (Jung et al., 2011). The shortness of implant may cause the deflection of implant axis during the insertion, which may damage the intra-bony threads and thus reduce the primary stability. Another cause for early implant failure may be related to the flapless technique used for implant placement (Sennerby et al., 2008). Shortcomings of flapless surgical procedure would be a greater potential for thermal trauma to the bone and the possibility of the deposition of epithelial or connective cells in the osteotomy site, which can interfere with osseointegration (Prithviraj et al., 2012). The failure incidences may also be related to bone quality in the mid-palatal region. Although recent work has shown adequate bone quantity and quality in the mid-palatal region to support implant placement (Siddiqi et al., 2012), there is little known about the risks of overheating bone in this anatomical site (Wiskott & Belser, 1999; Oh et al., 2002). A higher failure rate of implants in type I bone has been attributed to increased pressure on the osseous bed and overheating during implant installation (Truhlar et al., 1997).
Late failures occurred in the participants who exhibited loss of one or more of their crestal implants. This suggests that a patient-centered “cluster failure” effect may be partially responsible. Cluster failures can be related to local anatomic structure regarding bone quality and quantity or host related factors such as patients general health conditions (Ekfeldt et al., 2001). A finite element analysis (Chapter II, part 2) compared the stress/strain distribution in the peri-implant bone between the novel adopted implant distribution and conventional design in the maxilla. The results revealed a substantial load bearing capacity for mid-palatal implants shared by the most distal implant on the loaded side (Osman et al., 2013b). However, the recorded stress/strain values were within the physiological range of bone remodeling according to Frost’s Mechanostat theory. Thus, the question of whether the mechanical overloading has contributed to late implant failures or not remains debatable.

As indicated in Chapter IV, there were no significant differences in the prosthodontic maintenance between the titanium and zirconia implant overdentures, regardless of the specific jaw in which the dentures were located. The most prominent maintenance event encountered was overdenture fracture, which was different to the related implant overdenture literature. Wear and tear of attachment systems are known to be the most prevalent maintenance requirements for any type of implant overdenture. It has been suggested that with the mandibular two-implant overdenture design, the prosthesis rotates around an anterior fulcrum line or hinge-axis. These movements can clinically lead to plastic deformation and wear of the matrix, resulting in a reduction of retentive forces or fractures of the matrices. Our novel implant distributions reduced rotational overdenture movements, particularly in the mandible, thereby reducing the wear of the attachment systems (Osman et al., 2013 a). High impact resin was not used in our study and this may have affected the incidence of overdenture fractures. Thus, in future uptake of this approach we recommend the use of either high impact resin or a cobalt-chrome base in overdentures using this type of novel distribution. With the novel protocol, metal reinforcement may be used without the fear of implant overloading as the increased implant number will allow the load to be more widely distributed, thus improving the biomechanical situation (Sahin et al., 2002).

The lack of statistical significance in the matrix wear between the zirconia and titanium implant overdentures in this research does not necessarily negate the reality of clinical significance. Worn matrices were encountered in three participants, only in the zirconia group. Two participants experienced wear of all of their maxillary clips whereas the other participant experienced the opposite. It is speculated that the difference in the implant material may be
responsible for this increased tendency of matrix wear in the zirconia group. Zirconia is a much harder material than titanium and more liable to intra-oral aging with a subsequent increase in its surface roughness (Piconi & Maccauro, 1999). This may have contributed to the wear of matrices. However, before a definitive statement can be made, further in-vitro and in-vivo studies are needed to accept or refute this claim based on scientific evidence.

As identified in Chapter IV, three implants fractured in the zirconia group by the end of the one-year follow-up period as opposed to none in the titanium group. Unfavorable bending moments, associated with corono-apical bone resorption and loss of supporting bone, are suggested as the most probable cause of the implant fractures (Rangert et al., 1995). Another factor, which may have further contributed to the implant fracture, is the small implant diameter (ø 3.75 mm) and identical design of the zirconia implants to those of the titanium and insufficient attention to design optimization for the ceramic materials (Tagger Green et al., 2002). The higher incidence of implant fracture within the zirconia group compared to the titanium ones lends support to the wide spread notion among clinicians and patients that ceramics are mechanically inferior to metals as an implant material (Kohal et al., 2009b). Thus, future research in the biomaterial science should be directed towards design optimization of ceramic implants to improve its biomechanical integrity.

A qualitative study (Chapter VI) using semi-structured interviews was conducted to assess the patient-centered perceptions of the novel implant overdenture treatment protocol. The range of issues addressed included the patients’ satisfaction and perceived cost as well as the positive and negative aspects of the proposed treatment, along with considerations of implant materials and placement sites. The data was analyzed using a thematic analysis inductive approach (Burnard et al., 2008). This method allowed the generation of concepts, models or theories grounded in empirical data.

The outcomes of the qualitative study showed that implant treatment greatly improved the oral function and psychosocial aspects of edentulous patients, and consequently the quality of their life. Consistent with the findings of previous studies, cost was found to be a significant barrier for edentulous patients seeking implant treatment (Pommer et al., 2011; Müller et al., 2012). Previous experience with complete dentures (Emami et al., 2009), age of the patients (Tepper et al., 2003; Donnelly & MacEntee, 2012), and length of treatment were further factors that influenced decisions regarding prosthodontic rehabilitation. Contrary to expectations, the mid-palatal implant was not an issue from a patient’s point of view. The
majority of the patients did not find the presence of a mid-palatal implant objectionable, nor did it have an adverse effect on their speech pattern. The increased fit and retention of implant-supported overdentures as reported by patients can be considered as an ideal compromise for those patients who desire a fixed restoration but cannot access this treatment due to limited financial resources or anatomical considerations. This is particularly relevant when rehabilitating the mandibular ridge, where retention and fit of dentures is an issue of constant concern.

In Chapter V a detailed fractographic analysis using SEM allowed the identification of the possible causes of fracture of Y-TZP implants either during function or surgical placement. This included bending overload, manufacturing imperfections and implant design related factors, consistent with previous studies (Green et al. 2002; Virdee & Bishop, 2007). In all of the fracture incidences, the fractographic evidence revealed the presence of unfavorable bending and torquing forces on the implants. During the surgical placement, unfavorable bending forces were inadvertently created during hand torque use for the final placement of implants particularly in hard-type (I and II) bone. During function, the failure of some implants resulted in an implant number smaller than was originally planned. Furthermore, complex masticatory forces, particularly the non-axial component, exposed the implants to unfavorable flexure loading conditions. The presence of micron level machining defects detected in close association with stress concentration sites such as sharp re-entrants and thread notches at the crack initiation sites are strongly suggested to have compromised the tensile strength of ceramic implants and to have led to early implant failures (Andreiotelli & Kohal, 2009). Furthermore, the identical design of the zirconia implants to those of the titanium and insufficient attention to design optimization for the ceramics is suggested to have further contributed to the fracture events encountered. A design with sharp threads as well as internal line angles at the junction of the threads with implant body allowed for focal areas of high stress concentration and mechanical failure of implants (Piattelli et al., 1998).

Based on the observations of implant fracture during placement (Chapter V), recommendations were made for slight over-preparation of the implant site when dealing with a dense bone. This was argued to have the potential for minimizing the need for hand torquing of zirconia implants. Strict quality control during the manufacturing process to reduce inherent material imperfections cannot be overemphasized. Design considerations should be unique for ceramic implants and should address the brittle nature of the material. A thread design involving increased thread width, and decreased thread depth, as well as filleting of
internal line angles are suggested to be able to improve biomechanical integrity of zirconia implants.

**CONCLUSIONS**

Based on the findings of this *in-vivo* randomized clinical trial investigation and associated *in-vitro* research:

- Implant treatment greatly improves the oral function and psychosocial aspects of edentulous patients and this is positively reflected in their quality of life. Cost represents the main barrier that prevents patients from seeking implant treatment; mitigation of this through payment schemes, insurance or other third-party payment may increase acceptance of oral implants.
- The perception of some participants that zirconia as an implant material is healthier, more natural, and closer to bone in qualities than titanium materials supports the increasing popularity of the “metal-free concept” in some parts of the society and highlights the need for the development of alternative implant materials other than titanium.
- The incisive foramen may be considered an alternative implant site for the rehabilitation of the atrophic edentulous maxilla rather than the invasive augmentative procedures. However, due to the prosthodontic difficulties encountered with one-piece implants, the use of this implant site is recommended only with the conventional two-piece implants.
- The high failure rate observed for mid-palatal implants merits further investigations to evaluate the reasons behind these failures based on sound scientific evidence and cautions against the recommendation of this site for routine overdenture support.
- Mandibular tripodal design has the advantages of a removable prosthesis with increased amount of retention. The favorable clinical and prosthodontic outcomes found for posterior mandibular implants strongly support the application of this design; this is particularly relevant in young individuals where minimal posterior jaw bone resorption is anticipated.
- Slight over-preparation of the osteotomy site is recommended during the surgical placement of zirconia implant particularly in hard type (I and II) bone to minimize
bending and torquing stresses and potential fracture incidences during the surgical procedure.

- The increased incidences of matrix wear and implant fracture in zirconia group is a source of concern. Accordingly, the use of zirconia implants for overdentures support should be limited to the patients requesting or preferring a metal-free approach or those with proven allergy to titanium.

- Owing to the high failure rate observed for implants in the maxilla compared to the mandible, maxillary implant overdenture therapy should only be reserved to those cases exhibiting retention problems with conventional complete dentures. Accurate diagnosis and treatment planning is of the utmost importance to optimize treatment outcome. This should include the use of implant systems with well-established surface characteristics, selection of optimal implant recipient sites with adequate bone quantity and quality, and the use of conventional loading protocol to enhance the process of osseointegration.

- Design considerations for the zirconia implants should be unique relative to its mechanical properties. Focus should be on eliminating all the sharp line angles, filleting internal line angles, increasing the thread width and decreasing the thread depth.

**DIRECTIONS FOR FUTURE RESEARCH**

This research has shown that zirconia implant overdentures may be an option for the rehabilitation of completely edentulous patients who request a metal-free restoration or those who exhibit an allergy to titanium. However, future research is still necessary to identify the optimal implant design in terms of the implant taper, thread pitch, placement preparation and surface characteristics to ensure biomechanical integrity of the implant both during function and in surgical placement. Future research should focus on exploring different methods for attaining micro-surface characteristics on zirconia implants similar to those already established as optimum for osseointegration of titanium implants. Research and development should be in conjunction with commercial manufacturers focusing on scientific integrity and not on market share.

In terms of maintenance requirements, an increased tendency for matrix wear was observed with zirconia implants, thus parallel advancement in biomaterial research for novel
attachment systems compatible with ceramic implants is necessary. The reasons for this increased wear should be further investigated. The focus of complimentary biomaterial science research should also continue for the manufacture of two-piece zirconia implants. Two-piece zirconia implants would present a leeway space for many of prosthodontic maintenance issues that were encountered in this research.

Merits of the proposed novel implant distribution, particularly in the mandible, were apparent. However, strong scientific evidence to support its wider application is still lacking and clinical trials with conventional two-piece titanium implants are considered to be mandatory.
References


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