Zirconia- versus metal-based, implant-supported abutments and crowns

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Zirconia- versus metal-based, implant-supported abutments and crowns

Comparative studies on fracture mode and short-time clinical outcome

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CONTENTS

PREFACE

The present thesis is based on the following studies, which will be referred to in the text by their Roman numerals (I-IV):

Study I Hosseini M, Kleven E, Gotfredsen K. Fracture mode during cyclic loading of implant-supported single-tooth restorations. *Submitted.*

Study II Hosseini M, Gotfredsen K. A feasible, aesthetic quality evaluation of implant-supported single crowns: an analysis of validity and reliability. Clin.Oral Implants.Res. MAR 2011. *Epub ahead of print.*

Study III Hosseini M, Worsaae N, Schiødt M, Gotfredsen K. A comparative, three-year prospective study of implant-supported, single-tooth restorations of all-ceramic and metal-ceramic materials in patients with tooth agenesis. *Submitted.*

Study IV Hosseini M, Worsaae N, Schiødt M, Gotfredsen K. A one-year randomised, controlled trial of implant-supported, single-tooth restorations based on zirconia versus metal-ceramic. *Submitted.*

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ENGLISH SUMMARY

To restore oral functions in patients with missing teeth, single-tooth implants are a well-documented treatment option. Along with high survival rates, aesthetic factors have become an important clinical outcome variable for evaluating treatment success of implant-supported restorations. Thus, the selection of restoration materials should be based on proper optical characteristics in addition to biocompatibility and sufficient strength of materials. Abutments and crowns based on zirconia are one of the most recent alternatives to metal abutments and metal-ceramic crowns. To date, only few comparative studies have reported on aesthetic, biological, biomechanical and patient-reported outcomes of implant-supported single-tooth restorations of various biomaterials.

The aim of the present thesis was to investigate the clinical performance of zirconia-based implant-supported single-tooth restorations and to estimate long-term biomechanical results of zirconia-based versus metal-based restorations. The aim of study I was to analyse the mode of fracture and number of cyclic loadings until veneering fracture of zirconia-based all-ceramic restorations compared to metal-ceramic restorations. The aim of study II was to test the reliability and validity of six aesthetic parameters used at the Copenhagen Dental School to assess the aesthetic outcome of implant-supported restorations. The aims of study III and IV were to compare the influence of different abutment and crown materials on biological, biomechanical and technical, and professional- and patient-related aesthetic outcomes of implant-supported single-tooth restorations.

In the first study, the most frequent fracture mode was the veneering fracture, which was more severe at the all-ceramic than at the metal-ceramic restorations. Furthermore, more loading cycles until veneering fracture were registered at the metal-ceramic than at the all-ceramic restorations.

In study II, the overall intra- and inter-observer agreements for the six aesthetic parameters were substantial and moderate, respectively. The mucosal discolouration score had the highest intra- and inter-observed agreement. The six aesthetic parameters had a highly significant correlation to the corresponding VAS scores; thus, each parameter was found to be valid.

In study III and IV, all implants survived and the marginal bone loss was generally low. No significant differences in the mPlI and mBI at restorations of different abutment materials and in the marginal bone loss at restorations with zirconia and titanium abutments were recorded. In study III, the marginal bone loss at restorations with gold alloy abutments was significantly higher than at restorations with zirconia abutments. In study III and IV, the marginal adaptation of crowns was

significantly less optimal at the all-ceramic than at the metal-ceramic crowns. The loss of retention was the most frequent biomechanical complication and was mostly registered at the posterior regions. The veneering fracture was slightly more frequent at the all-ceramic than at the metal-ceramic crowns. The crown colour match was significantly better at all-ceramic versus metal-ceramic crowns, while no significant difference in the other aesthetic parameters between various restoration materials were observed. The patient-reported satisfaction with aesthetic outcomes was not significantly different at restoration of various materials, and it was not significantly correlated to the professional-reported aesthetic outcomes.

Conclusion: The biological outcome variables were similar at the different abutment materials; however, the marginal bone loss was higher at the gold alloy compared to the zirconia and titanium abutments. The biomechanical and technical outcome variables were more optimal at the metal-ceramic than at the zirconia-based all-ceramic restorations. The six aesthetic parameters used in our studies were feasible, reliable and valid, which make them useful for quality control of implant-supported single-tooth restorations. The use of these aesthetic parameters indicated no remarkable difference in aesthetic outcome of restorations with various abutments materials, but the all-ceramic crowns provided a better colour match than the metal-ceramic crowns. The patients did not notice difference in the aesthetic results of restorations of various materials.

DANSK RESUMÉ

Behandling med enkelttandsimplantater er en veldokumenteret behandlingsform for at genskabe de orale funktioner hos patienter med manglende tænder. De æstetiske faktorer er, ud over en høj overlevelsesprocent, blevet vigtige klinisk variabler for vurdering af behandlingssuccesen af implantatunderstøttede restaureringer. Derfor bør valget af restaureringsmaterialer være baseret på deres optiske egenskaber foruden deres biokompatibilitet og tilstrækkelig materialestyrke. Abutment og kroner baserede på zirkonia er et af de nyeste alternativer til metal abutment og metalkeramiske kroner. I dag er der kun få studier, der har sammenlignet og rapporteret de æstetiske, biologiske, biomekaniske og patientrelaterede resultater af implantatunderstøttede enkelttandsrestaureringer af varierende biomaterialer.

Formålet med denne afhandling var at undersøge den kliniske ydeevne af zirkonia-baserede implantatunderstøttede enkelttandsrestaureringer, og at estimere biomekaniske langtidsresultater af zirkonia-baserede versus metalkeramiske restaureringer. Formålet med studie 1 var at sammenligne frakturmønstret og antallet af cykliske belastninger indtil fraktur af påbrændingskeramikken mellem zirkonia-baserede og metal-baserede restaureringer. Formålet med studie 2 var at undersøge påligeligheden og gyldigheden af seks æstetiske parametre, som var anvendt til vurdering af det æstetiske resultat af implantatunderstøttede restaureringer på Tandlægeskolen i København. Formålene med studie 3 og 4 var at sammenligne effekten af forskellige abutment- og kronematerialer på de biologiske, biomekaniske og tekniske samt på de professional- og patient-rapporterede æstetiske resultater af implantatunderstøttede enkelttandsrestaureringer.

Ved den første studie var fraktur af påbrændingskeramikken den hyppigste frakturmønster, som var mere omfattende ved de helkeramiske end ved de metalkeramiske restaureringer. Desuden var flere belastningscykler indtil fraktur af påbrændingskeramikken registreret ved de metalkeramiske end ved de helkeramiske restaureringer.

I studie 2 var den overordnede intra- og inter-observatør enighed for de seks æstetiske parametre henholdsvis substantiel_og moderat. Den højeste intra- og inter-observatør enighed var registreret ved scoren for misfarvning af mukosa. De seks æstetiske parametre havde en signifikant korrelation til de tilsvarende VAS scorer og var derfor gyldige.

I studie 3 og 4 overlevede alle implantater og marginalt knoglesvind var generelt lavt. Forskellen i mPlI og mBI var ikke signifikant ved restaureringer af forskellige abutment materialer, og heller ikke forskellen i marginalt knoglesvind var signifikant mellem restaureringer med zirkonia og titan

abutment. I studie 3 var marginalt knoglesvind signifikant større ved restaureringer med guldlegering end ved dem med zirkonia abutment. I studie 3 og 4 var marginalt tilpasning af zirkonia-baserede helkeramiske kroner mindre optimal end de metalkeramiske kroner. Den hyppigste biomekaniske komplikation var kroneløsning, som ofte var registreret i de posterior regioner. Frakturen af påbrændingskeramikken var lidt hyppigere ved de helkeramiske end ved de metalkeramiske kroner. Kronefarven var signifikant bedre ved de helkeramiske end ved de metalkeramiske kroner, mens de andre æstetiske parametre ikke var signifikant forskellige ved diverse restaureringsmaterialer. Patienternes tilfredshed med det æstetiske resultat var ikke signifikant forskellig ved restaureringer af forskellige materialer og var ikke signifikant korreleret til de professionelles vurdering af det æstetiske resultat.

Konklusion: De biologiske resultater var sammenlignelige ved forskellige abutment materialer, dog var marginalt knoglesvind større ved abutment af guldlegering end ved zirkonia abutment. De biomekaniske og tekniske resultater var mere gunstige ved de metalkeramiske end ved de zirkonia-baserede helkeramiske restaureringer. De seks æstetiske parametre brugt i vores studier var gennemførlige, pålidelige og gyldige, hvilket gør dem anvendelige for kvalitetskontrol af implantatunderstøttede enkelttandsrestaureringer. Anvendelse af disse parametre viste ingen betydelige forskelle i det æstetiske resultat af restaureringer med forskellige abutment materialer, men de helkeramiske kroner udviste en bedre farvematch end de metalkeramiske kroner. Patienterne bemærkede ikke forskel i det æstetiske resultat mellem restaureringer af forskellige materialer.

ABBREVIATIONS

AC	All-ceramic
AC-C	All-ceramic crown on ceramic abutment
AC-M	All-ceramic crown on metal abutment
CAD/CAM	Computer-aided design/ Computer-aided manufacturing
CDA	California Dental Association
CEI	Complex Esthetic Index
CIS	Copenhagen Index Score
DES	Mesio-distal distance in edentulous space
ICA	Implant Crown Aesthetic index
ISP	Implant-supported premolar crown
ISSC	Implant-supported single crown
mBI	Modified sulcus Bleeding Index
MC	Metal-ceramic
MC-M	Metal-ceramic crown on metal abutment
mPlI	Modified Plaque Index
OHIP	Oral Health Impact Profile
PES	Pink Esthetic Score
PPD	Probing Pocket Depth
RCT	Randomised Clinical Trial
VAS	Visual Analogue Scale
WES	White Esthetic Score
Y-TZP	Yttria-stabilized tetragonal zirconia polycrystal

INTRODUCTION

In modern prosthetic dentistry, the major purpose is to assure oral function for the individual patient. Oral functions include mastication, aesthetics and psycho-social abilities, occlusal support and dental arc stability, and other functions such as tactile perception, phonetics and taste [1].

To restore oral functions in patients with missing teeth, single-tooth implants are a well-documented treatment option [2-4]. Along with good survival rates, aesthetic factors have become an important clinical outcome variable for evaluating treatment success of implant-supported restorations [5]. When restoring missing teeth with implant-supported restorations in aesthetic demanding regions, selection of abutment and crown materials is one of the possibilities to achieve an optimal aesthetic result. Abutments and crowns based on zirconia are one of the most recent alternatives to metal abutments and metal-ceramic crowns. It may be hypothesised that implant-supported single-tooth restorations with zirconia abutments and all-ceramic crowns will result in a better clinical outcome than metal abutments and metal-ceramic crowns, but to confirm it comparative studies have to be performed. To date, only few comparative studies have reported on aesthetic, biological, biomechanical and patient-reported outcomes of implant-supported, single-tooth restorations of various biomaterials.

Abutment and crown materials in implant dentistry

Titanium, gold alloys and oxide ceramics are the abutment material options in implant dentistry [6]. Traditionally, implant-supported restorations included titanium abutments and metal-ceramic crowns. Metal abutments have been suggested to shine through mucosa and induce a greyish appearance of peri-implant soft tissue [6-14]. To improve the aesthetic outcome and to enhance the colour harmony between restorations and natural dentition, high-strength oxide ceramics, mainly zirconia, has been introduced as implant abutment and crown core materials [5, 7, 8, 10, 13, 15, 16]. Due to opaque colour of oxide ceramics, crown core of zirconia must be veneered with more translucent ceramic materials to imitate the natural tooth colour. However, only few *in vitro* and *in vivo* studies have compared implant-supported, single-tooth restorations of metal-ceramic materials with zirconia-based abutments and crowns [17, 18].

Ceramics

The increased requirement of improving aesthetic properties of restorations is one of the principal driving forces behind a rapid development of tooth-coloured dental restorative materials [19, 20]. Ceramic materials represent one of the few choices for tooth-coloured restorative treatments and are considered as one of the most biocompatible dental materials with relative low incidence of biological side effects [19, 21].

Dental ceramics can be classified at a microstructure level by their composition of glass-to-crystalline ratio (Table 1) [22].

Table 1: Classification of dental ceramics

Classifications		**Main composition**	**Flexural strength (MPa)***
Glass-based systems	Feldspathic porcelains	Silica (SiO_2)	70–100
Glass-based systems with fillers	Low-to-moderate leucite-containing feldspathic glass	Silica with fillers, fillers usually crystalline (leucite, lithium-disilicate, flourapatite)	120–300
	High-leucite (~50%)-containing glass, glass-ceramics		
	Lithium-disilicate (~70%) glass-ceramics		
Crystalline-based systems with glass fillers	Infiltration ceramics	Alumina or zirconia-toughened alumina with glass fillers	> 300
Polycrystalline solids	Oxide ceramics	Alumina (Al_2O_3)	275–700
		Zirconia (ZrO_2)	800–1500

* Milleding P, Karlsson S, Molin M. Dentala helkeramer i teori och klinik. Stockholm: Gothia, 2005.

Glasses in dental ceramics originate principally from a group of mined minerals called feldspar. Feldspathic porcelains are primarily composed of silica (SiO_2), alumina (Al_2O_3) and various amount of K_2O and Na_2O [19, 22, 23]. In order to improve the mechanical properties of dental ceramics, crystals have either been added to or grown in glass matrix (glass-ceramics). In general, more glass in the microstructure results in more translucent ceramic, while more crystals gives more opaque appearance. Glass-based ceramic materials are highly aesthetic materials with best optical properties, and they tend to be employed as veneer materials for metal or ceramic substructures [22, 23].

Other ceramic materials are mainly used as substructures and have been developed to fulfil the aesthetic and high mechanical requirements. Aluminium oxide (alumina) and zirconium dioxide (zirconia) represents the high-strength, polycrystalline oxide ceramics with densely packed crystals and no glassy components. Zirconia has a higher fatigue-crack propagation threshold than alumina, and it has a fracture toughness that is at least twice higher than alumina [24].

In clinical studies of implant-supported single-tooth restoration, fracture of veneering ceramics has been reported as a frequent problem [2, 25, 26]. Only one recent *in vitro* study has investigated a possible difference in veneering fracture of implant-supported single crowns (ISSCs) when glass-ceramic and feldspathic porcelain were used [27]. Thus, more comparative *in vitro* and *in vivo* studies of ISSCs with various types of veneering ceramics are needed.

Yttria-stabilized tetragonal zirconia polycrystals (Y-TZP)

The superior mechanical properties of zirconia make this material suitable for biomedical application, especially in implant dentistry [28]. The key factor for biomechanical properties of zirconia is phase transformation of crystals [24]. The crystalline state of zirconia is monoclinic at room temperature and occupying approximately 4.5% more volume than a tetragonal crystalline state at firing temperature (1170^{o}C to 2370^{o}C). The tetragonal form of crystals is stabilized at room temperature by addition of Y_2O_3 (yttria) [28, 29]. The yttria-stabilized tetragonal zirconia polycrystals (Y-TZP) is “metastable”, and stress-generating surface treatment such as grinding and sandblasting as well as stress concentration at tip of a propagating crack are able to trigger transformation of material back to the monoclinic state [29]. The subsequent increasing volume leads to surface compression and increase flexural strength and susceptibility to aging [24, 29]. Low temperature degradation of zirconia aggravated by presence of water is a well-documented phenomenon [23, 29, 30]. However, only few long-term clinical studies of zirconia-based abutment and crowns supported by implants are published [31]. Thus, the influence of the microstructural transformations of zirconia on clinical performance of implant-supported single-tooth restorations is still unknown.

Biomechanical and technical aspects

During masticatory function, dental restorations are exposed to fatigue under repeated loading in wet environment [32]. Repeated contact loading reduces the strength and limits the useful life-time of all ceramic materials, which occurs mostly in veneering ceramics but even to some degree in Y-TZP substructrures [33]. During cyclic loading test, brittle ceramic materials are in an active stress intensity in a higher time-average than at static loadings under equivalent loading conditions; therefore, cyclic loadings causes greater damage in ceramic materials [33].

To study the biomechanical strength and the fracture mode of ceramic materials and in attempts to link *in vivo* and *in vitro* studies, inclusion of intraoral conditions such as cyclic loadings and presence of water to laboratory study protocols are required [32, 34]. Despite of these recommendations, several *in vitro* studies of implant-supported restorations have used static load-to-fracture tests [35-40]. Consequently, fractures of components such as screws and abutments have frequently been reported [35-40]. As these laboratory study results are in contrast to clinical findings, the clinical relevance of static load-to-fracture test protocol could be questioned [2, 25, 31, 34, 41, 42].

In clinical studies of implant-supported restorations, veneering fracture has been reported as one of the most common biomechanical complications [25, 26, 31, 43]. The clinical failures of all-ceramic restorations are complex and involve both patient- and material-related variables [44]. To compare the traditionally implant-supported restorations of metal abutments and metal-ceramic crowns with restorations of zirconia abutments and zirconia-based all-ceramic crowns, the well-controlled laboratory studies are useful to eliminate the inter-subject variability.

Biological aspects

Biocompatibility involves the effects of material on the medium and *vice versa*. Biomaterials and their degradation products should not induce inflammatory reactions, allergic, immune, toxic, mutagen or carcinogenic reactions [28]. Zirconia has been used as orthopaedic hip implant material in more than 20 years [30, 45], and the great biocompatibility of this material has been demonstrated in various *in vitro* and *in vivo* studies [46].

In implant dentistry, zirconia has mainly been used as an alternative material for metal abutments and substructures of fixed prostheses. As the transmucosal part of abutment is located close to the alveolar bone, the soft tissue integration and the marginal tissue reaction to the abutment material is important for stability of the peri-implant bone level [47]. The abutment material has been shown to influence the quality of epithelial attachment, and it has been indicated that the choice of abutment material must be based on its ability to promote soft-tissue integration and maintain a healthy peri-implant mucosa [48, 49].

The well-known high biocompatibility of titanium abutments has been the major reason to use this material as a "golden standard" to compare biological properties of different abutment materials. In an experimental study in dogs, zirconia abutments established a similar mucosal attachment as titanium abutments, while gold alloy abutments achieved no proper soft tissue integration [48]. Degidi et al. [50] compared inflammatory reactions in biopsies from peri-implant tissues around zirconia and titanium healing caps, and they demonstrated more inflammatory infiltrates in soft tissue around titanium than around zirconia healing caps. In the study by Welander et al. [48], the proportion of leucocytes at barrier epithelium was lower at zirconia abutments compared to titanium abutments, and this difference was proposed to be related to variations in bacterial plaque accumulation on titanium and zirconia abutment surfaces [48]. It is noteworthy that oral plaque accumulation has been suggested to be one of the major reasons of implant failure [51]. In *in vivo* studies by Rimondini et al. [45] and Scarano et al. [52], significantly less accumulation of plaque on zirconia compared to titanium surfaces was detected. Based on these observations, it was suggested that zirconia was a suitable material for abutment fabrication [45, 52].

However, clinical studies are valuable to compare the biological outcome of different abutment materials. In a four-year prospective clinical study by Vigolo et al. [53], no biological variation between gold alloy and titanium abutments were detected, which is in contrast to the results of the animal studies by Abrahamsen et al. [49] and Welander et al. [48]. In a 3-year randomized clinical study by Zembic et al. [17], the comparison of customized zirconia and titanium abutments demonstrated no significant differences in biological parameters between zirconia and titanium abutments. Thus, more comparative, clinical data are needed to draw a definite conclusion on effect of abutment materials on peri-implant tissue.

Aesthetic aspects

Aesthetics seems to be one of the main reasons why patients seek prosthetic treatment [1]. The standards for aesthetic fixed implant prosthesis have been defined as healthy peri-implant tissues with natural appearance of restorations in harmony with the healthy surrounding dentition [54, 55]. Thus, restorations should be selected not only base on appropriate biological properties and sufficient strength to withstand the masticatory forces but also based on proper optical characteristics to provide an optimal aesthetic result [20, 56].

The great long-term survival rate of single-tooth implants [3, 25, 31, 57, 58] is one of the reasons to more focus on aesthetic outcome of implant-supported single crowns [59-61]. Since the development of metal-ceramic crowns in the early sixties, these restorations have represented the “golden standard” in prosthetic dentistry [62, 63]. A progressive introduction of high-strength oxide ceramics, especially zirconia, with white colour and “relative translucency”, has generally resulted in an increased use of metal-free restorations [64]. In implant dentistry, the use of zirconia-based, implant-supported restorations is suggested to enhance the colour match of restorations with natural teeth and to decrease the grayish appearance of peri-implant mucosa [20]. A high standard of aesthetic quality is particularly important at implant-supported, single crowns as an immediate visual comparison of the implant-supported crown with the surrounding natural dentition is possible [5, 65]. To have an insight in the aesthetic result of a specific treatment and to facilitate analysis of results in order to improve the prosthetic treatment, the use of rating scores with a division in different items have been recommended [66]. Thus, a feasible, valid and reliable rating score is required to compare the aesthetic outcome of zirconia-based, all-ceramic and metal-ceramic implant-supported, single-tooth restorations.

In the dental literature, the California Dental Association (CDA) index [67] has frequently been used [43, 68, 69]. This index includes five parameters, whereas two, i.e. anatomic form and colour match are suitable to describe implant-supported single crowns. To describe the aesthetics of peri-implant soft tissue, Jemt [70] introduced simple scores including the papilla index scores as well as scores for presence or absence of soft tissue discolouration and presence or absence of visible titanium margins.

To assess the aesthetic outcome of implant-supported single crowns, a number of other categorical rating scores have been developed during the last decade (Table 2). Some of these rating scores, e.g. Implant Esthetic Score [71] and Pink Esthetic Score [59] concentrate only on aesthetic outcome of peri-implant tissue. Other scores, e.g. Implant Crown Aesthetic Index [66] and a score comprised of modified Pink Esthetic Score and White Esthetic Score [72] as well as the scores used at the Dental School in Copenhagen [73] include also the aesthetic parameters of implant-supported restorations. Some of these scores, e.g. the Implant Crown Aesthetic Index, are very detailed and comprehensive indices, but they appears to be the most difficult to use [74]. Additionally, reliability and, in particular, validity of some of these rating scores have not been tested in clinical settings. The test of reliability of scales is necessary in establishing the usefulness of a measure, but it is not sufficient. The validity of scales should be determined to draw an accurate conclusion about the presence and degree of the attribute. This could be performed by analysing the correlation of a scale with a ‘golden standard’, which has been used and accepted in the field [75]. Visual Analogue Scale

(VAS) is a continuous scale and has also been used to assess the aesthetic outcome of implants by dentists in some studies [65, 76, 77]. As this scale has most often been used as a measuring instrument for dental, dentofacial, or facial aesthetics [78] VAS could be used as a "golden standard" to validate the categorical aesthetic parameters.

Table 2. Overview of studies introducing categorical rating scores for aesthetic assessment of implant-supported single crowns

Study	**Index**	**Parameters (number of scores)**	**Reliability & validity**
Meijer et al. [66]	Implant Crown Aesthetic Index (ICA)	- Mesiodistal dimension of the crown (5 scores) - Position of the incisal edge of the crown (5 scores) - Labial convexity of the crown (5 scores) - Colour and translucency of the crown (3 scores) - Surface of the crown (3 scores) - Position of the labial margin of the peri-implant mucosa (3 scores) - Position of mucosa in the approximal embrasures (3 scores) - Contour of the labial surface of the mucosa (5 scores) - Colour and surface of the labial mucosa (3 scores)	+ reliability [66, 79] - validity
Fürhauser et al. [59]	Pink Esthetic Score (PES)	- Mesial papilla (3 scores) - Distal papilla (3 scores) - Level of soft tissue margin (3 scores) - Soft tissue contour (3 scores) - Alveolar process deficiency (3 scores) - Soft tissue color (3 scores) - Soft tissue texture (3 scores)	+ reliability [80] - validity
Testori et al. [71]	Implant Aesthetic Score (IES)	- Presence and stability of the mesiodistal papilla (3 scores) - Ridge stability bucco-palatally (2 scores) - Texture of the peri-implant soft tissue (3 scores) - Color of the peri-implant soft tissue (3 scores) - Gingival contour (3 scores)	- reliability - validity
Dueled et al. [73]		*Aesthetic of crowns* - Crown morphology (4 scores) - Crown colour match (4 scores) *Facial aesthetic* - Symmetry/harmony (4 scores) *Aesthetic of mucosa* - Mucosal discolouration (4 scores) - Mesial papilla (4 scores) - Distal papilla (4 scores)	+ reliability [81] + validity [81]

Belser et al. [72]	Modified PES and White Esthetic Score (PES/WES)	*Modified PES* - Mesial papilla (3 scores) - Distal papilla (3 scores) - Level of facial mucosa (3 scores) - Curvature of facial mucosa (3 scores) - Root convexity/ soft tissue color and texure (3 scores) *WES* - Tooth form (3 scores) - Outline and volume of crown (3 scores) - Color (hue and value) (3 scores) - Surface texture (3 scores) - Translucency and characterization (3 scores)	- reliability - validity
Juodzbalys & Wang [82]	Complex Aesthetic Index (CEI)	*S* - Soft tissue contour variations (3 scores) - Soft tissue vertical deficiency (3 scores) - Soft tissue color and texture variations (3 scores) - Mesial papillae appearance (3 scores) - Distal papillae appearance (3 scores) *P* - Mesial interproximal bone (3 scores) - Distal interproximal bone height (3 scores) - Gingival tissue biotype (3 scores) - Implant apico-coronal position (3 scores) - Horizontal contour deficiency (3 scores) *R* - Color and translucency (3 scores) - Labial convexity in the abutment/implant junction (3 scores) - Implant/crown incisal edge position (3 scores) - Crown width/length ratio (3 scores) - Surface roughness and ridges (3 scores)	+ reliability [82] - validity

Patient-related aspects

The aesthetic outcome is *a priori* very subjective and should be assessed both by the patient and the dentist. It has been recommended that dentist and patient should plan the aesthetic treatment together [83, 84]. However, the aesthetic evaluations by the patient should be more focused than the professional assessment [65, 74, 85].

In a number of clinical studies of implant-supported restorations, questionnaires have been used to register the patient-reported aesthetic outcome [3, 65, 69, 73, 74, 76, 86-88]. In these studies, the patients judged the appearance of the restorations on either a VAS [3, 65, 69, 76, 87, 88] or on a categorical scale varying from two to six scores [73, 74, 86, 87]. In spite of variations in aesthetic questions and their assessment methods, it was generally indicated that the patients were highly satisfied with the aesthetic result of their implant-supported single crowns [3, 69, 73, 74, 76, 86-88], and the dental professionals were more critical than patients on this outcome variable [73, 74, 76, 86-88]. Based on these deviations between patient- and professional-reported aesthetic outcomes, it was proposed that the subjective patient evaluation is of primary importance for the assessment of a successful outcome in implant dentistry [89]. As one of the major reasons for using all-ceramic restorations is to improve the aesthetic result, the assessment of patient´s opinion on appearance is even more important when comparing implant-supported all-ceramic and metal-ceramic restorations. To date, only one randomized clinical study has compared patient-reported aesthetic outcome of implant-supported, all-ceramic with metal-ceramic single crowns [18]. Hence, more clinical studies are needed to evaluate any differences in patient´s aesthetic satisfaction between implant-supported single crowns of different materials.

AIMS

The specific objectives of the studies in the thesis were:

- to compare the mode of fracture and number of cyclic loadings until veneering fracture of all-ceramic and metal-ceramic restorations supported by implants (study I).

- to test the reliability and validity of the aesthetic parameters used at the Copenhagen Dental School and to compare the professional- and patient-reported aesthetic outcomes (study II).

- to compare the influence of abutments of zirconia (study III & IV), titanium (study III & IV) and gold alloy (study III) on biological outcome variables of implant-supported single-tooth restorations.

- to compare the impact of all-ceramic and metal-ceramic restorations on biomechanical and technical outcome variables of implant-supported, single-tooth restorations (study III & IV).

- to compare the impact of restoration materials on the professional- and patient-reported aesthetical outcome variables of implant-supported, single-tooth restorations (study III & IV).

MATERIAL AND METHODS

A summary of the material and methods used in the four studies is presented in Table 3.

Table 3. Design, number of subjects and materials used in the *in vitro* and *in vivo* studies

	Study I		Study III		Study IV (&II*)	
Study design	*In vitro* 4.2 mill cyclic loadings		*In vivo* 3-year, prospective study		*In vivo* 1-year, randomized study	
No. patients	-		59		36	
Mean age (range)	-		27.9 (18-50)		28.1 (19-57)	
No. of ISSCs	32		98		75	
Implant position - Incisors - Canines - Premolars -Molars	 - - - -		 42 26 29 1		 - - 75 -	
Type of ISSCs (no.)	AC (16)	MC (16)	AC (52)	MC (46)	AC (38)	MC (37)
Abutment materials (no.)	Zirconia (16)	Titanium (16)	Zirconia (52)	Titanium (21) Gold alloy (25)	Zirconia (38)	Titanium (35) Gold alloy (2)
Coping materials (no.)	Zirconia (16)	Gold alloy (16)	Zirconia (49) Glass-ceramic (3)	Gold alloy (34) Zirconia (12)	Zirconia (38)	Gold alloy (37)
Veneering ceramics (no.)	Feldspathic (8) Glass-ceramic (8)	Feldspathic (8) Glass-ceramic (8)	Glass-ceramic (52)	Glass-ceramic (46)	Feldspathic (34) Glass-ceramic (4)	Feldspathic (34) Glass-ceramic (3)

* In study II, clinical photographs of 34 patients also participating in study IV were included.
ISSC: Implant-supported single crown
AC: All-ceramic ISSC
MC: Metal-ceramic ISSC

Fracture mode during cyclic loading (study I)

In this *in vitro* study, 32 implant-supported single crowns (ISSCs) were inserted in acrylic resin blocks. Two test groups of all-ceramic (AC) restorations and two control groups of metal-ceramic (MC) restorations were prepared.

All abutments had prefabricated preparations and were prepared with an angle of 45 degrees at the palatal aspect in the upper part. The abutments were tightened to the implants with a torque of 25 Ncm by using a torque wrench. All crowns were manufactured as canines with a palatal inclination of 45 degree (Figure 1).

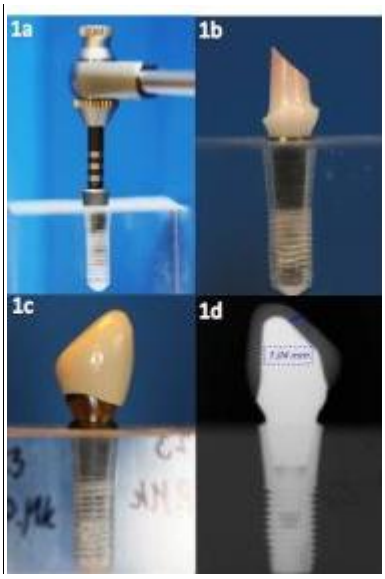

Figure 1. Illustration of an implant insertion in acrylic block (1a), prepared abutment (1b) and the crown design (1c and 1d)

Based on a great number of pilot tests, fracture mode 0 (no fractures) to 7 (implant fracture) were categorized (Table 4, Figure 2) and the test method was developed.

The study samples were subjected to cyclic loading in a test machine constructed to and used in studies by Isidor et al. [90, 91] and Sahafi et al. [92]. The cyclic loadings were performed with a stainless steel ball with a diameter of 6 mm directed to the palatal surface of the crowns, 1.5 mm below the incisal edge. The loading angle was 15 degree to the long axis of implants. During the cyclic loadings, the restorations were kept under humid conditions with distilled water. The loading force was set to 800 N with a frequency of 2 Hz. and continued to 4.2 million cycles or until fracture of copings, abutments or implants. The number of cyclic loadings and fracture modes were recorded. The first recorded fracture mode was the initial fracture, and the final fracture mode was the fracture after 4.2 mill cycles or the fracture of coping, abutment or implant.

Table 4. Fracture modes

Fracture modes	Descriptions by visual examination
0	No fractures, flaws or infractions
1	Infraction in veneering ceramic
2	Chip-off within veneering ceramic (Cohesive fracture)
3	Fracture of veneering ceramic with exposure of coping
	Fracture mode 3.a: fracture <½ of veneering ceramic
	Fracture mode 3.b: fracture ≥ ½ of the veneering ceramic
4	Fracture of both veneering ceramic and coping without abutment fracture
5	Fracture of coping and abutment
6	Fracture of abutment without crown fracture
7	Fracture of implant

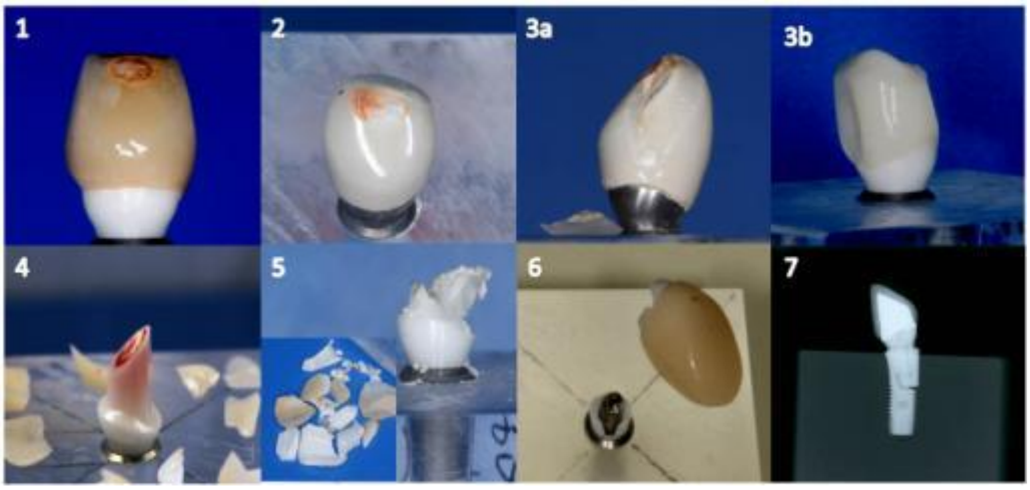

Figure 2. Illustration of the fracture modes. The numbers indicate the corresponding fracture mode.

Design of clinical studies (study II, III and IV)

The clinical studies (study II, III & IV) included patients with tooth agenesis referred to the School of Dentistry in Copenhagen for prosthetic treatments. The inclusions criteria were all patients, who required replacements with implant-supported, single crowns (ISSCs), had no contraindications for oral implant treatment, e.g., uncontrolled diabetes, metabolic bone disorders, history of radiotherapy in head and neck, current chemotherapy or other diseases with an influence on bone healing, and participated in 1-year (study II & IV) and 3-year (study III) follow-up examinations.

All implants (Astra Tech®, Mölndal, Sweden) were inserted at The Department of Oral and Maxillofacial Surgery, Glostrup University Hospital (Copenhagen, Denmark). After an implant healing period of 4–6 months, the prosthetic procedures were initiated at the School of Dentistry in Copenhagen.

In study III, the patients were consecutively included between 2005 and 2008. The treating prosthodontists decided the use of AC and MC restorations. Fifty-nine patients; 35 women and 24 men; fulfilled the inclusion criteria and were rehabilitated with 98 ISSCs; 52 AC and 46 MC restorations.

In study IV, all patients had tooth agenesis in the premolar regions, and the prosthetic treatments were randomised between AC and MC restorations. The study protocol was accepted by the Danish Regional Committee on Biomedical Research Ethics. Thirty-six patients (18 men and 18 women) were included and restored with 75 ISSCs; 38 AC and 37 MC restorations.

In study II, the clinical photographs of 66 ISSCs of 34 out of the 36 patients in the study IV were included to assess the aesthetic outcomes.

Follow-up examinations (study III and IV)

The patients were recalled to baseline (study III & IV), 1-year (study IV) and 3-year (study III) follow-up examinations. The clinical and radiological registrations were performed, and biological, biomechanical and technical, aesthetic and patient-reported variables were recorded (Table 5).

Table 5. Outcome variables registered at the clinical studies (III & IV)

	Variables	Description	Baseline	Follow-up ≥1 year	Study
Biological	Implant survival[1)]	Implants still in function	X	X	III & IV
	Implant mobility[1)]	Clinical absence of mobility	X	X	III & IV
	- Modified Plaque Index (mPlI) [2)] - Modified Sulcus Bleeding Index (mBI)[2)]	Median values of mPlI and mBI scores assessed at four sites of each ISSC	X X	X X	III & IV
	Complications - Neurosensory disturbance - Devitalisation of adjacent teeth - Inflammatory reactions; fistula, exudation/suppuration or pain		 X X X	 X X X	III & IV
	- Marginal bone loss≥ 2 mm		-	X	III
	- Marginal bone loss≥ 1.6 mm - PPD≥ 5mm		- X	X X	IV
	Marginal bone level	Most coronal bone-implant contact mesially and distally	X	X	III & IV
	Marginal bone loss	Mean value of change in mesial and distal marginal bone level	-	X	III & IV
	Interproximal marginal bone width	Mean values of distance between neighbouring teeth and implants	X		III
	Orthodontic pretreatment	Orthodontic treatment before implant insertion	X	-	III
	Apical root resorption of adjacent teeth[3)]	Absence: apical root score 0 and 1 Presence: score 2, 3 or 4	X		III

Biomechanical and technical	Crown and abutment survival	Crowns and abutments still in function	X		X	III & IV
	Cement excess	Radiopaque particles detected on radiographs at the ISSCs	X		X	III & IV
	Marginal adaptation[4)]	Radiological evaluation of marginal fit of the crowns, score 1 to 4		X		III & IV
	Complications					III & IV
	- Loosening or fracture of the abutment screws		X		X	
	- Loss of retention		X		X	
	- Fracture including chipping of the veneering ceramics		X		X	
Aesthetic	Copenhagen Index Score	Each of five parameters: score 1 to 4 [4)]				III & IV
	- Crown morphology score			X		
	- Crown colour match score			X		
	- Mucosal discolouration score		X		X	
	- Papilla index score, mesially		X		X	
	- Papilla index score, distally		X		X	
	CIS (summary score)	Overall professional-reported aesthetic outcome	X		X	
	Mesio-distal distance in the edentulous space (DES)	Minimum coronal distance between the proximal surfaces facing to the implant site	X		-	III & IV
Patient-reported	Danish version of Oral Health Impact Profile questionnaire[5)] (OHIP-49)	Aesthetic outcome: summary of scores from question 3, 4, 20, 22, 31 and 38[4)]	X		X	III
		Masticatory outcome: summary of scores from question 1, 28, 29 and 32[6)]	X		X	
		Overall impact of oral health on life quality: summary score of 49 questions	X		X	
	Visual Analogue Scale (VAS)	Overall aesthetic outcome of each restoration	-		X	IV

1) Albrektsson, T. & Isidor, F. Consensus report of session IV. In: Lang NP, Karring T, eds. Proceedings of the 1st European workshop on periodontology. Berlin: Quintessence Publ.Co.Ltd. 1993; 365-369
2) Mombelli A, van Oosten MA, Schurch E Jr, Land NP. The microbiota associated with successful or failing osseointegrated titanium implants. Oral Microbiol.Immunol. 1987; 2:145-151
3) Malmgren, O., Goldson, L., Hill, C., Orwin, A., Petrini, L. & Lundberg, M. (1982) Root resorption after orthodontic treatment of traumatized teeth. Am.J.Orthod. 82: 487-491.
4) Dueled E, Gotfredsen K, Trab DM, Hede B. Professional and patient-based evaluation of oral rehabilitation in patients with tooth agenesis. Clin.Oral Implants.Res. 2009; 20:729-736
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6) Goshima, K., Lexner, M.O., Thomsen, C.E., Miura, H., Gotfredsen, K. & Bakke, M. Functional aspects of treatment with implant-supported single crowns: a quality control study in subjects with tooth agenesis. Clin.Oral Implants.Res. 2010; 21: 108-114.

Biological variables (study III and IV)

The clinical examinations included registration of implant survival and mobility, the modified Plaque Index (mPlI) and the modified Sulcus Bleeding Index (mBI) [93] at four aspects of each ISSCs.

Furthermore, complications were registered (study III & IV) and it was recorded whether or not the patients had received orthodontic treatments previously (study III).

The radiological assessments of marginal bone level (study III & IV) and interproximal marginal bone widths (study III) were performed (Figure 3). The absence or presence of apical root resorption of the neighbouring teeth was recorded [94] (study III).

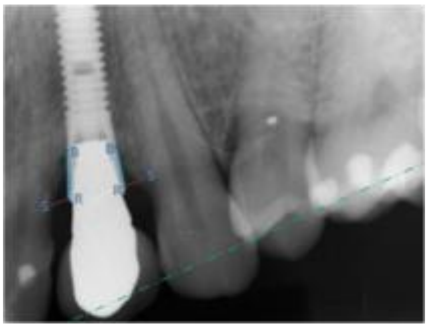

Figure 3. The marginal bone level was determined by measuring the distance between a reference point at the top of the implant (R) and the most coronal bone-implant contact (B).
The interproximal marginal bone width was measured as the distance between R and S (surface of the neighbouring

Reproducibility of radiographic measurements (study III)

To estimate the intra-observer reproducibility, the radiographs of 20 included implants were randomly selected, and the mesial and the distal marginal bone levels at the baseline and the 3-year examination were re-examined four weeks after the first assessments. The mean difference between 80 repeated measurements was 0.02 mm, SD 0.34; thus, the "limits of agreement" varied from -0.65 to + 0.69 mm (i.e., 95% of the differences in the repeated measurements are expected to lie within this interval).

Biomechanical and technical variables (study III and IV)

The clinical examinations included crown survival and registration of loosening or fracture of the abutment screws, loss of retention and fracture including chipping of the veneering ceramics.

Radiographs were examined to record cement excess mesially and/or distally at the implants and to evaluate marginal fit of the crowns using a modified marginal adaptation score [73] ranging from 1 to 4: score 1 was excellent fit, 2 was distinguish misfit, 3 was distinct misfit, and 4 was unacceptable misfit (Figure 4). The marginal adaptation score of each ISSC restoration corresponded to the highest score detected on radiographs from both follow-up examinations.

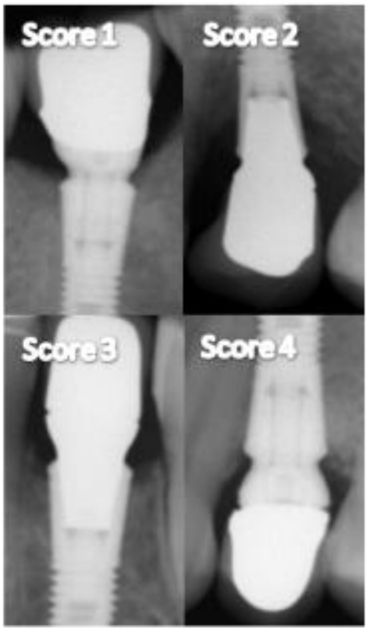

Figure 4. Radiological illustration of marginal adaptation score 1 to 4

Aesthetic variables, professional-reported (study II, III and IV)

The aesthetic outcome of the ISSCs was evaluated by using the Copenhagen Index Score [73, 81]. In study II, all six aesthetic parameters, i.e. crown morphology, crown colour match, harmony/symmetry score, mucosal discolouration score and papilla index score, mesially and distally were included. In study III and IV, five out of the six aesthetic scores (without the harmony/symmetry score) were used. All scores varied from 1 for excellent to 4 for poor aesthetic result. The overall professional-reported aesthetic outcome was expressed by summary of all included scores, i.e. the six scores in study II and the five scores in study III and IV.

The aesthetic parameters were assessed by using the photographs taken at the follow-up examinations (study II, III & IV) combined with the clinical registrations (study III & IV).

Furthermore, cast models fabricated before crown cementation were used to measure the mesio-distal distance in the edentulous space (DES) as the minimum coronal distance between the proximal surfaces facing the implant site.

Validity and reliability of Copenhagen Index Score (study II)

The extra- and intra-oral photographs of the 66 implant-supported premolar crowns were used to evaluate the six aesthetic parameters of the Copenhagen Index Score as well as VAS (Visual Analogue Scale) scores—a 100 mm line with the end phrases ‘‘very bad aesthetic’’ on the left and ‘‘very good aesthetic’’ on the right. The VAS scores and summary of scores of six aesthetic parameters (CIS score) were used to mark the overall impression of the aesthetic results.

One undergraduate dental student and two prosthodontists, one experienced and the other non-experienced, evaluated all photographs twice with an interval of 1 week. In addition, 10 dental students were randomly divided into two groups and asked to rate the aesthetic outcomes of the crowns only once.

To test the convergent validity, the observer with the highest internal consistency marked the general impression of each six aesthetic parameters used to define the current index separately on the VAS.

Patient-reported outcomes (study II, III and IV)

A possible impact of oral health-related quality of life was evaluated by the patients using the Danish version of the Oral Health Impact Profile questionnaire (OHIP-49) before the prosthetic treatment and at the follow-up examinations (studies II & III). Each question answer was scored with the Likert response scale from 0 (never experienced problem) to 4 (problem experienced very often). The summary of questions 3, 4, 20, 22, 31 and 38 was used to describe the patient-reported aesthetic outcome [73] (study II & III), and the masticatory function was expressed by the summary scores of questions 1, 28, 29 and 32 [95] (study III). The overall oral health impact on quality of life was described by a summary of the scores from all 49 OHIP questions (study III). For patients with more than one restoration, the mean of summary scores was used.

In study IV, the patients assessed the overall aesthetic outcome of each ISSC in the premolar regions by a Visual Analogue Scale (VAS) at the 1-year examination.

Statistical analysis

The statistical analyses were performed with an SAS 9.1 package. The statistical significance level was set at $P < 0.05$.

Study I

The initial and final fracture modes were analysed by descriptive analysis and Mann-Whitney test by using ranks corresponding to increasing severity. The Cox proportional hazards analysis where used to analyze the differences in loading cycles until fracture mode ≥ 3a.

Study II

Reliability

To test the reliability of Copenhagen Index Score, intra-observer agreements and weighted Cohen's κ were calculated for the experienced and non-experienced prosthodontists, and for the undergraduate dental student.

The inter-observer agreements were calculated between (i) experienced prosthodontist and non-experienced prosthodontist (ii) experienced prosthodontist and student, (iii) non-experienced prosthodontist and student and (iv) two groups of five students.

Additionally, stability was tested by calculating the mean of intra- and inter-observer Cohen's k for pooled parameters, and the internal consistency was analysed by the Cronbach α.

Validity

The Spearman's test was used to correlate the overall aesthetic results measured by VAS to the CIS values. To test the convergent validity, the six aesthetic parameters were correlated to the corresponding VAS scores.

Study III and IV

To account for the correlation between several restorations applied to the same patient, models had to incorporate a random subject level. For the quantitative data (e.g., marginal bone loss and DES), evaluation was performed by using a traditional mixed model of ANOVA. For ordinal categorical data (differences in mPlI, mBI, marginal adaptation score and professional-reported aesthetic scores), a nonlinear mixed model was applied using PROC NLMIXED [96].

The logistic regression model was used to analyze the relation between the presence and absence of apical root resorption at neighbouring teeth and the number of tooth agenesis for patients who received orthodontic pretreatment (study III).

Patient-reported outcome

To analyze the difference of aesthetic outcomes in patients with different restoration materials, the non-parametric one-way ANOVA was performed (study III). In study IV, the difference in patient-reported aesthetic VAS scores between AC and MC restorations (excluding the harmony/symmetry score) was analyzed by using mixed model of ANOVA.

To analyse the correlation between the professional- and patient-reported aesthetic outcomes, the Spearman's correlation analysis was performed (study II & III).

SUMMARY OF RESULTS

Study I

Fracture mode during cyclic loading of implant-supported single-tooth restorations

In this *in vitro* study, veneering fracture was the most frequently observed fracture mode for the AC as well as the MC restorations. All MC restorations resisted 4.2 million cyclic loadings without coping and/or abutment fracture. In contrast, 6 out of the 16 AC restorations did not resist 4.2 million cyclic loadings as they fractured in coping and abutment.

The statistical differences in fracture modes and number of loading cycles until veneering fracture (≥3a) between restorations of various materials are demonstrated in Table 6. Significantly more loading cycles until the veneering fracture were estimated, when the MC-I restorations were compared to the AC-I and MC-H restorations.

Figure 5 illustrates that, although no significant difference in the number of loading cycles between the AC and the MC restorations was detected, more loading cycles were needed before the MC restorations fractured in the veneering ceramics.

Table 6. P-values for Mann-Whitney test for distribution of initial and final fracture modes (using ranks corresponding to increasing severity), and for Cox proportional hazards analysis to estimate the differences in loading cycles at fracture mode ≥ 3a

	Initial fracture mode (*P*-value)*	**Final fracture mode (*P*-value)***	**Loading cycles until fracture mode ≥ 3a (*P*-values)#**
AC-H vs. MC-H	0.720	0.061	0.592
AC-I vs. MC-I	0.003	0.007	0.038
AC vs. MC	0.010	<0.001	0.161
AC-H vs. AC-I	0.791	0.238	0.565
MC-H vs. MC-I	0.019	0.049	0.036

* Mann-Whitney analysis
# Cox proportional hazards analysis
AC: All-ceramic restoration (AC-H and AC-I)
MC: Metal-ceramic restoration (MC-H and MC-I)
AC-H: AC restorations veneered with HeraCeram Zirconia
AC-I: AC restorations veneered with IPS e.max Ceram
MC-H: MC restorations veneered with HeraCeram
MC-I: MC restorations veneered with IPS d.SIGN

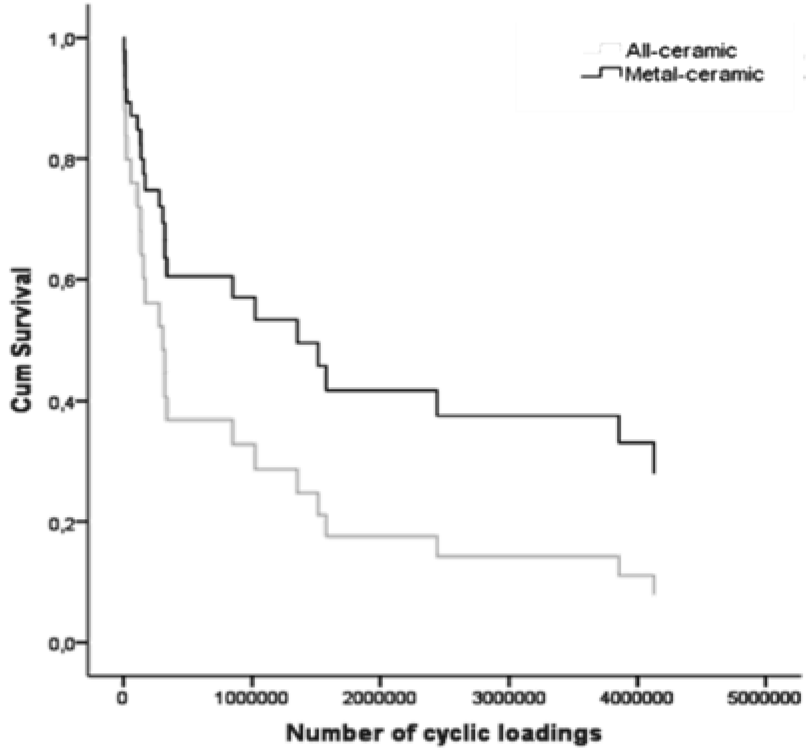

Figure 5. Estimated number of cyclic loadings until fracture of the veneering ceramics (fracture mode ≥ 3a); all-ceramic (AC, n=16) vs. metal-ceramic (MC, n=16) restorations

Study II

A feasible, aesthetic quality evaluation of implant-supported single crowns: an analysis of validity and reliability

Reliability

The intra-observer agreement and weighted Cohen´s κ are presented in Table 7. The mucosal discolouration score had generally the highest observed agreement, and the crown morphology rated by prosthodontists and the distally papilla index score evaluated by the student had the lowest frequency of agreement.

The weighted Cohen´s κ demonstrated that the highest intra-observer agreement was for the papilla index score, mesially, evaluated by both prosthodontists (substantial), and for the crown colour match evaluated by the student (substantial). The intra-observer agreement was substantial for the mucosal discolouration score for all observers.

The Cronbach α for the experience prosthodontist, non-experienced prosthodontist and undergraduate student was 0.84, 0.87 and 0.85, respectively.

Table 8 demonstrates the inter-observer agreement and weighted Cohen´s κ. The mucosal discolouration score had the highest frequency of inter-observed agreement and the highest Cohen´s κ (moderate in all observations). The mean of intra- and inter-observer Cohen´s κ for pooled parameters was 0.53 (stability test).

Validity

A significant correlation between the CIS and the overall VAS scores were observed (Table 9). The six aesthetic parameters showed a highly significant correlation to the corresponding VAS scores.

Patient- and professional-reported aesthetic outcomes

No significant correlations between the overall professional VAS scores and CIS to the summary scores of the six OHIP questions were found.

Table 7. Intra-observer agreement and Cohen´s κ (weighted) for all 6 aesthetic parameters

Parameters	Assessment I vs. II					
	Experienced		**Non-experienced**		**Student**	
	Observed agreement (%)	Cohen's κ	Observed agreement (%)	Cohen's κ	Observed agreement (%)	Cohen's κ
Crown morphology	72.2	0.63	68.2	0.52	66.7	0.54
Crown color match	80.3	0.32	74.2	0.61	84.1	0.72
Symmetry/harmony	79.3	-0.04	78.1	0.64	59.7	0.56
Mucosal discolouration	84.8	0.66	81.8	0.70	84.1	0.69
Mesial papilla	78.8	0.72	80.3	0.76	66.7	0.57
Distal papilla	72.7	0.53	68.2	0.59	50.0	0.46
All six parameters	75.6	0.64	75.1	0.67	68.6	0.63

Table 8. Inter-observer agreement and Cohen´s κ (weighted) for all six aesthetic parameters

Parameters	**Experienced vs. Non-experienced** Assessment I & II		**Experienced vs. student** Assessment I & II		**Non-experienced vs. student** Assessment I & II		**Two student groups** Assessment I	
	Observed agreement (%)	Cohen's κ	Observed agreement (%)	Cohen's κ	Observed agreement (%)	Cohen's κ	Observed agreement (%)	Cohen's κ
Crown morphology	49.2	0.23	53.8	0.32	49.3	0.27	47.4	0.38
Crown color match	59.1	0.25	53.8	0.15	63.6	0.44	50.0	0.31
Symmetry/harmony	62.9	0.15	40.2	0.15	57.8	0.45	47.9	0.33
Mucosal discolouration	75.7	0.51	81.1	0.59	79.5	0.60	63.8	0.53
Mesial papilla	54.5	0.40	60.6	0.50	66.6	0.56	56.2	0.44
Distal papilla	58.3	0.40	45.8	0.39	52.7	0.42	61.7	0.47
All 6 parameters	60.0	0.42	56.5	0.43	60.6	0.51	54.0	0.42

Table 9. The six aesthetic parameters correlated to corresponding Visual Analogue Scale (VAS) scores, and Copenhagen Index Score (CIS) correlated to the overall VAS score (n=66)

	r_s	95% CI	*P*
Crown morphology	-0.54	-0.7 to -0.35	<.0001
Crown colour match	-0.63	-0.77 to -0.46	<.0001
Symmetry/harmony	-0.79	-0.9 to -0.62	<.0001
Mucosal discolouration	-0.57	-0.72 to -0.38	<.0001
Mesial papilla	-0.77	-0.86 to -0.65	<.0001
Distal papilla	-0.62	-0.76 to -0.45	<.0001
CIS	-0.61	-0.75 to -0.43	<.0001

r_s: Spearman's rank correlation coefficient; CI: Confidence interval

Study III

A comparative, 3-year prospective study of implant-supported, single-tooth restorations of all-ceramic and metal-ceramic materials in patients with tooth agenesis

Biological variables

All implants survived after 3 years and only one implant with a marginal bone loss of 2.5 mm did not fulfil the radiographic success criteria. The measured marginal bone loss was generally low but significantly (*P*=0.040) higher at implants supporting the gold alloy abutments (0.41 mm, SD 0.58) compared to those supporting the zirconia abutments (0.15 mm, SD 0.25) (Figure 5). At the 3-year examination, 2 buccal marginal and 3 buccal apical fistulas were registered (Figure 6).

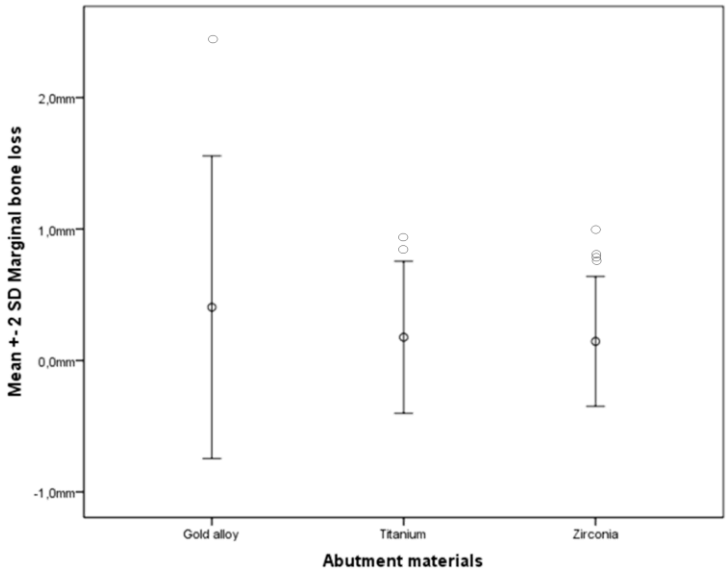

Figure 5. Mean, 2SD and outliers of marginal bone loss at sites with gold alloy, titanium and zirconia abutments

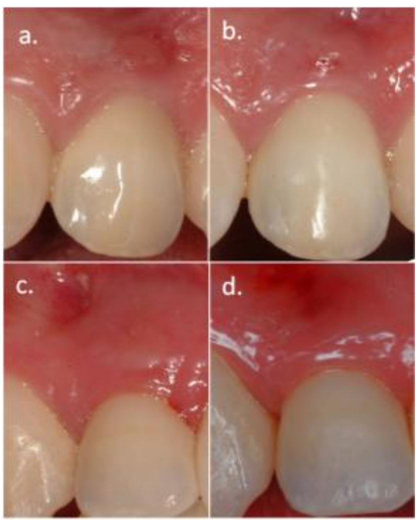

Figure 6. Buccal marginal fistula at baseline (a), reduced at the 3-year observation (b).
Buccal apical fistula in combination with exfoliation of bone graft materials at the baseline (c), reduced at the 3-year observation (d)

Fifty out of 59 patients had received orthodontic pretreatment, and the apical root resorptions (score 2 or more) were registered in at least one neighbouring tooth to the implants in 31 of these 50 patients (62%). None of the 9 patients without a history of orthodontic pretreatment demonstrated apical root resorption.

Biomechanical and technical variables

The survival rate of the abutments and crowns was 97%. There was registered: 3 crowns with loss of retention (3 MC restorations; all recemented), 2 fractures of veneering ceramic (2 AC restorations; 1 polished and 1 remade) and 2 unacceptable marginal adaptations (1 AC and 1 MC restorations; both remade).

Excesses of cement materials were observed at 4 ISSCs, where the marginal bone loss was only demonstrated at one of these restorations with a marginal adaptation score 2. No significant relation between cement excess and mBI was found. Marginal adaptation scores were significantly lower at the metal-ceramic compared to the all-ceramic crowns (P= 0.020).

Professional-reported aesthetic variables

No significant differences in the crown morphology scores, the mucosal discolouration scores and the papilla index scores, mesially and distally between the all-ceramic and the metal-ceramic restorations were observed. The scores of the crown colour match were significantly (P= 0.015) lower at the all-ceramic than at the metal-ceramic crowns.

While the frequency of score 1 for the mucosal discolouration decreased, it increased for the papilla index scores at the zirconia and the metal abutments from the baseline to the 3-year observation.

Patient-reported variables

The patient-reported satisfaction with aesthetic outcome, masticatory function and overall oral health impact on quality of life increased, i.e. the OHIP scores decreased, during the course of the study.

The means of summary scores on six aesthetic OHIP questions were not significantly different between patients treated with various restoration materials.

The professional- and patient-reported aesthetic outcomes at the 3-year follow-up were not significantly correlated (r_s=0.21, P=0.18).

Study IV

A 1-year randomised, controlled trial of implant-supported, single-tooth restorations based on zirconia versus metal-ceramic

Biological variable

All implants survived and no mobility was recorded after one year of function. The mean marginal bone level at the baseline examination was significantly (P= 0.034) more apically positioned at the AC (mean 0.58 mm, SD 0.62) than at the MC restorations (mean 0.33 mm, SD 0.33). At the 1-year examination, the mPlI and mBI as well as the mean marginal bone loss was not significantly different at the AC and the MC restorations (AC: mean 0.08 mm, SD 0.25, MC: mean 0.10 mm, SD 0.17).

At the 1-year examination, biological complications, e.g. fistula, exudation/suppuration, pain or PPD≥ 5 mm, were detected at 10 restorations, 7 AC restoration, of which 5 had a marginal adaptation score 2, and at 3 MC restorations, all with a marginal adaptation score 1 (Figure 7).

Figure 7. Marginal adaptation score 2 at all-ceramic (AC) restoration in region 34, and clinically observation of suppuration at 1-year examination.

Biomechanical and technical variables

The survival rate of the abutments as well as the crowns was 98.7%. At the 1-year examination, 2 complications at 2 MC restorations were registered; one chipping of veneering ceramic (Figure 8) and one loss of retention. The restoration with loss of retention was remade.

Cement excess was observed at 1 MC restoration with a marginal adaptation score 2 and a marginal bone loss of 0.53 mm.

The marginal adaptation scores were significantly (P= 0.014) lower at the MC compared to the AC restorations (Figure 9).

Figure 8. Photographs of a metal-ceramic crown (region 25) at the baseline examination, and chip-off fracture of the veneering ceramic recorded at the 1-year examination.

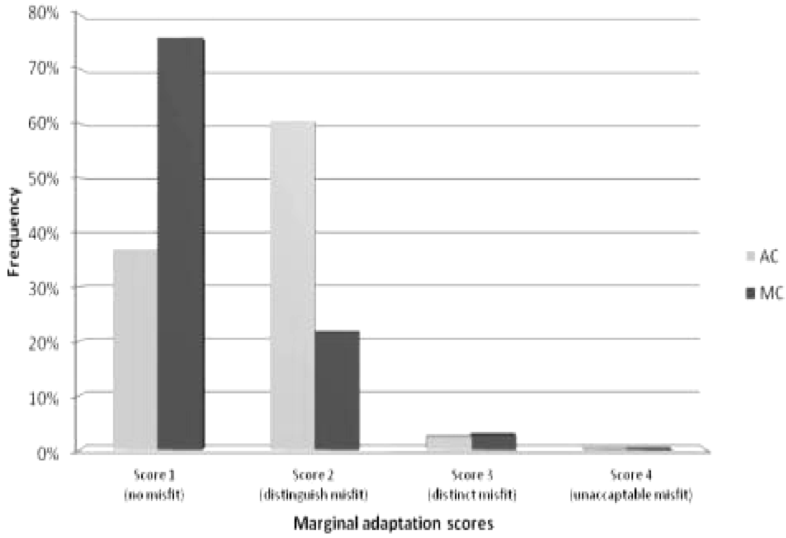

Figure 9. The frequency of the marginal adaptation scores at restorations with the all-ceramic (AC) and the metal-ceramic (MC) crowns.

Professional-reported aesthetic variables

The crown morphology scores, mucosal discolouration scores, the papilla index scores, mesially and distally, and CIS were not significantly different at the AC and the MC restorations.

The crown morphology scores increased significantly (P<0.0001) with higher DES values. The frequency of the mucosal discolouration scores was almost unchanged for AC and MC restorations, but the frequency of the papillae with score 1, mesially and distally increased at the AC and the MC restorations from baseline to 1-year registration.

The crown colour match scores were significantly (P=0.031) lower at all-ceramic crowns than at the metal-ceramic crowns.

Patient-reported aesthetic variables

The VAS scores were not significantly different between the AC and the MC restorations (AC: mean 84.9, SD 18.4, MC: mean 83.1, SD 18.8).

No significant correlation between the CIS (professional-reported) and VAS (patient-reported) was found. However, the VAS scores increased significantly with lower scores of the crown colour match, crown morphology and papilla index, mesially.

DISCUSSION

Titanium abutments and metal-ceramic crowns have been used as “golden standards” for restorations supported by dental implants. Although other restoration material options have been introduced and used in clinical settings, only few comparative *in vitro* and *in vivo* studies have reported on different implant-supported restoration materials using traditional titanium abutments and metal-ceramic crowns as control. The clinical studies in the present thesis intended to investigate the clinical performance of zirconia-based implant-supported single-tooth restorations, and the *in vitro* study was designed to estimate the biomechanical long-term results of these restorations compared to titanium abutments and metal-ceramic crowns. Furthermore, the biological outcome of gold alloy abutments was analysed. A feasible aesthetic index was tested for reliability and validity, and it was used to assess the professional-reported aesthetic outcome of all-ceramic crowns and abutments compared to metal-ceramic crowns and metal abutments. The patient-reported aesthetic outcomes of implant-supported restorations were recorded and correlated to the professional-reported aesthetic outcomes.

Influence of restoration materials on peri-implant tissue

Implant survival and success rate

In the present clinical studies with 1 and 3 year follow-up examinations, the survival rate of implants in function was 100%, which is in accordance with the reported, estimated annual implant failure rate varying from 0% to 2.5% [31]. After 3 years of oral function, the radiological success rate of implants supporting titanium and zirconia abutments was 100%. Only one implant that supported a gold alloy abutment and an all-ceramic crown with a radiological registered marginal misfit did not fulfil the success criteria as the marginal bone loss was more than 1.9 mm after 3 years of function [97]. The misfit of the all-ceramic crown could be one of the variables that influenced marginal bone loss at this implant.

Marginal bone loss and plaque accumulation

The marginal bone loss during the present clinical studies was comparable at the zirconia and titanium abutments after 1 and 3 years, but it was highest at gold alloy abutments. These findings agrees with the experimental animal studies by Abrahamsson et al. [49] and Welander et al. [48], which also detected more marginal bone loss associated with gold alloy abutments, than at abutments of oxide ceramics and titanium. In addition, in a systematic review of clinical studies of implant-supported restorations by Sailer et al. [31], the rate of marginal bone exceeding 2 mm was higher for implants supporting metal than for those supporting ceramic abutments. In that systematic review, the metal abutments referred to both gold alloy and titanium abutments, and ceramic abutments referred to oxide ceramics, i.e. alumina and zirconia abutments.

In contrast, similar marginal bone loss at titanium and gold alloy abutments were reported in a four-year clinical study of ISSCs [53]. It should be noticed that in our prospective clinical study, the gold alloy abutments were mainly used in situations, where abutments were angulated to compensate for buccal positioning of implants. This may have led to more marginal bone loss at the implants supporting gold alloy abutments than at the implants supporting zirconia and titanium abutments. It has also to be emphasized that the differences in marginal bone loss were small. The overall annual marginal bone loss was less than 0.1 mm in both clinical studies, which agrees with the corresponding values reported in a 10-year prospective study of Astra Tech implants by Gotfredsen [3]. Furthermore, the minor changes in the peri-implant marginal bone level during our clinical studies were within the limits of variability for our radiological measurement method.

In order to compare the plaque accumulation on zirconia and titanium abutments, Rimondini et al. [45] and Scarano et al. [52] reported on lower accumulation as well as colonization of bacterial plaque on zirconia than on titanium surfaces. The amount of plaque in our clinical studies was generally low and none of the abutments had a supramucosal exposure to the oral cavity. These clinical conditions may be the reasons for no significant difference in plaque accumulation at restorations with different abutment materials in the present clinical studies. This finding also agrees with another clinical 3-year follow-up study of all-ceramic and metal-ceramic implant-supported restorations [17].

Biological complications

The most frequent biological complications at the marginal peri-implant soft tissue were fistulas and suppuration observed during the 3-year prospective and the 1-year randomised clinical study, respectively. Fistulas at implant sites have been associated with insufficient marginal adaptation of crowns [76], cement excess [4], apical pathology of neighbouring teeth [98] or screw loosening [99]. The apical buccal fistulas in the present prospective study were related to inflammatory reactions originated from necrosis of the neighbouring tooth and to exfoliation of bone substitutes from buccally augmented site. The buccal marginal fistulas as well as the suppuration in our clinical studies were mainly registered at the restorations with all-ceramic crowns with suboptimal marginal adaptation. It is well-known that marginal misfit at the crown and abutment interface may establish a space for bacterial colonization and cause chronic inflammation and subsequent breakdown of the surrounding tissue [100].

Even though apical root resorption is a consequence of implant insertion, it is most likely a complication induced by the orthodontic pretreatment. All patients in our clinical studies had tooth agenesis, and the radiographic examinations in the prospective study demonstrated apical root resorption in at least one neighbouring tooth to implants in 62% of patients who underwent orthodontic pretreatments. The role of tooth agenesis as a factor to increase the risk of apical root resorption during orthodontic treatment is not clear [101, 102]. However, the orthodontic treatment to provide the required space for implants had a significant influence on the prevalence of apical root resorption in our study. This finding is consistence with a comparable study of a similar group of patients with tooth agenesis by Dueled et al. [73].

Biomechanical and technical complication at different restoration materials

Crown and abutment survival and failure rates

The survival rates of crowns and abutments in the study III and IV were 96.9%, and 98.7%, respectively. The annual failure rates of crowns and abutments in the study III and IV were 1.02% and 1.33%, respectively, which are within the range of the estimated annual failure rate for ISSCs reported by Jung et al. [25].

When all ISSCs in both current clinical studies were pooled, the survival rate of the all-ceramic restorations was 97.8% which was comparable with the survival rate of the metal-ceramic crowns on metal abutments (98.6%). In the systematic review study by Sailer et al. [31], the survival rate for either types of restorations was 100%, however, the number and follow-up period of studies reporting on the all-ceramic restorations were less than the studies reporting on the metal-ceramic restorations. As all zirconia-based ISSCs in the posterior regions survived in our clinical studies as well as in the study by Zembic et al. [17], these restorations may be a suitable alternative to the traditional metal-ceramic restorations also in the posterior regions at least for short-time.

No complications during the present clinical studies involved the abutments, but when crowns were remade new abutments were used for practical reasons. In a study by Aboushelib & Salameh [103], a few clinical cases of zirconia abutment fractures were analysed, and it was assumed that the over-reduction of axial wall thickness of abutments, incorrect position of abutments and tightening of screws beyond the recommended torque as well as fabrication defects could contribute to zirconia abutment fractures. Generally, fracture of metal as well as ceramic abutments have been reported as a seldom complication in clinical short-time studies [25, 31]. According to these systematic reviews, screw loosening has been reported as the most common biomechanical and technical complication of ISSCs. However, in our studies and in the clinical study by Zembic et al. [17], no screw loosening were observed which may be explained by the use of a torque wrench for tightening of all abutment screws. In earlier prospective studies performed before the introduction of torque wrenches higher frequencies of screw loosening have been reported [99, 104, 105]. The time period may also have a great impact on the number of screw loosening.

Loss of retention, cement excess

The most frequent biomechanical complication in our clinical studies was the loss of retention. The annual failure rate of this complication was 1.02% and 1.33% in study III and IV, respectively. The loss of retention has also been reported as the second most frequent biomechanical complication of ISSCs with an estimated annual rate of 1.13% [25], and with no significant difference between crowns supported by ceramic versus metal abutments [31]. Nevertheless, in our clinical studies, this complication was mainly observed at metal-ceramic crowns in the posterior regions. The lower height of the abutments in these regions and consequently minor mechanical retention as well as higher forces and moments acting in the posterior regions [95] may have contributed to the occurrence of this complication.

The radiological registrations in our clinical studies demonstrated five ISSCs with sub-mucosal excess of cement materials. Marginal bone losses at sites with excess of cement were only observed at restorations with suboptimal marginal adaptation of crowns and no significant relation between cement excess and mucosal inflammation measured with mBI was found. In other clinical studies, the cement excess has been related to the occurrence of fistulas [4] and to the clinical signs of the peri-implant diseases [106]. However, in our studies, the presence of cement excess was only registered radiographically, and the amount of cement excess registered at the radiographs was limited.

Marginal adaptation

The radiological assessments of the marginal adaptation in our clinical studies demonstrated that the frequency of misfit at the interface between the crowns and abutments was significantly higher at the restorations with zirconia-based, all-ceramic crowns than at those with metal-ceramic crowns. In an *in vitro* study by Tao & Han [107] as well as in a clinical study by Reich et al. [108], the marginal gaps at zirconia-based, all-ceramic restorations were greater than at metal-ceramic restorations, which agrees with the results of the present clinical studies. However, contrasting results were reported in another laboratory study by Gonzalo et al. [109].

One of the explanations of the differences in the marginal adaptation between the all-ceramic and metal-ceramic crowns in the current studies may be linked to the differences in the fabrication procedures of these crowns. The enlarged pre-sintered zirconia copings should be sintered after the milling process to obtain the final strength, which results in shrinkage of the material. As this process is sensitive, it may result in deformation of restoration and marginal adaptation [110]. Additionally, the subsequent porcelain veneering process may also have influenced the marginal adaptation of the zirconia copings [111-113].

Marginal adaptation may, however, also be related to oblique seating of crowns [114] and the clinical procedures with modelling of the tight proximal contacts [115]. This should however be the same procedure for the all-ceramic and the metal ceramic crowns.

Veneering fracture

In the present clinical studies, the annual rate of veneering fracture was 0.68% after 3 years (study III) and 1.33% after 1 year (study IV) of function, which were almost in the same range as the estimated annual rate for this complication reported by Jung et al. [25]. In our clinical studies, the veneering fractures were registered at one metal-ceramic and at two all-ceramic restorations. In agreement with our results, a higher rate of veneering fracture was reported in studies of all-ceramic crowns than studies of metal-ceramic crowns [25].

Laboratory test method

In spite of a high frequency of veneering fractures reported in short-term clinical studies of ISSCs [25, 31, 41, 42], the long-term clinical performance of zirconia-based abutments and crowns are still unknown. In the present *in vitro* study, a clinical relevant laboratory method, which was developed to induce veneering fracture, was used to compare the fracture of the all-ceramic and metal-ceramic restorations during simulated long-term masticatory function. The method was set up to avoid abutment, abutment screw and implant fractures, which are frequently observed in the laboratory studies using load-to-fracture tests [37-40]. All zirconia abutment fractures in the current study occurred as a consequence of coping fractures and were preceded by veneering fractures. The use of loading force of 800 N was high, but within the range of maximal measured bite forces [95, 116, 117]. The 4.2 million cyclic loadings corresponds to at least 16 years of clinical function [118], or according to Kelly [34], this number of loading cycles at 800 N represents at least four years of constant bruxism under extreme load. In a number of laboratory studies using lower loading forces or less number of loading cycles, no fractures were developed [37, 40, 119]. It may be argued that the frequency of extreme high loadings used in the present study were more than most subjects will experience. Additionally, abutment fractures were very seldom registered with the used loading direction, which can be interoperated as a good long-term strength of the titanium as well as the zirconia abutments. In an *in vitro* study by Cho et al. [120], it was demonstrated that the fracture strength of ISSCs was significantly higher at the metal-ceramic than at the all-ceramic restorations, and fracture strength increased significantly at a vertical compared to an oblique loading direction. Furthermore, the fractographic analysis in an *in vitro* study by Aboushelib et al [121] demonstrated that the chip off fractures were caused by e.g. surface defects, improper support by substructure or overloading and fatigue. Although the restorations were exposed to high loading forces and fatigue in our *in vitro* study, the low frequency of chip off fractures could be linked to the loading direction and the structural support of veneering ceramic.

Fracture mode

In the present *in vitro* study, the fracture modes and the number of cyclic loadings until the veneering fractures were influenced by the different core and veneering materials. The most frequent fracture modes, i.e. the veneering fractures, were more severe at the all-ceramic than at the metal-ceramic restorations. Furthermore, more loading cycles until the veneering fractures were registered at the metal-ceramic than at the all-ceramic restorations. These results could be explained by a lower bonding strength at the zirconia-ceramic than at the metal-ceramic interface and indicated that the core-veneer interface in zirconia-based restorations was the weakest part of these restorations [122, 123]. However, the difference in bonding strength between core materials of zirconia and metal to the veneering ceramics was not significant in another *in vitro* study [124]. In addition to insufficient bonding between veneering and coping, the fractures of veneering ceramics have been assumed to be related to residual stress after firing and to polishing of veneering ceramics [44, 125, 126].

Differences in bonding strength between different veneering ceramics to the same core materials have also been reported. Thus, in a laboratory study, the bonding strength of the glass-ceramics was higher than the bonding strength of the feldspathic ceramics to the metal core materials [127]. In the current study, the fractures of restorations with feldspathic veneering ceramics were more severe than those veneered with glass-ceramics; however, this difference was not demonstrated in a recent laboratory study using another test method [27]. As a result of a limited number of restorations used in the present *in vitro* study, the interpretation of the results should be done with caution.

Aesthetic parameters at different crown and abutment materials

The professional-reported aesthetic outcomes of all-ceramic and metal-ceramic restoration in the clinical studies in this thesis included five aesthetic parameters. The reliability and validity of these parameters in addition to the score of symmetry/harmony were analysed.

Reliability of aesthetic parameters

Reliability is a basic requirement of scales and it plays an essential role in judgment of adequacy of any measurement process [75]. The acceptable level of reliability is not clearly defined and should be related to the clinical situation and the measured variable [75]. The six aesthetic parameters in our studies were based on the standards for an aesthetic fixed implant restoration [55], i.e. the harmony with the perioral facial structures was defined by using the symmetry/harmony score, the aesthetic of peri-implant tissue was defined by the mucosal discolouration score and the papilla index scores, and the natural appearance of the restorations by the scores of crown colour match and crown morphology. The crown morphology and colour match scores used in our studies were adapted from the CDA criteria [67]. The crown morphology and symmetry/harmony scores included several sub-parameters and demonstrated a relatively low reliability in study II. Although a better test–retest reliability could have been achieved with more unambiguous definition of these scores, e.g. by separation into more parameters, this will result in a less feasible index. In the ICA index [66], the crown morphology was divided into several parameters, however, this scale also demonstrated limitations in reliability [79].

The crown colour match score used in the present studies had a relatively high intra-observer agreement. In the WES, developed by Belser et al. [72], this parameter composed of the score for colour (hue/value) and the score for translucency/characterization, but the reliability and validity of these scores were not analysed. In our study, the high reliability of crown colour match score may be caused by the quality evaluation of crowns performed by the treating dentists. As the crowns with suboptimal or poor colour were sent to colour corrections, it could led to a high frequency of crowns with colour match score 1 and 2. For crown morphology score, however, the mesio-distal space for each crown was an important factor and might have restricted the quality evaluation made by the dentists.

The mucosal discolouration parameter had generally the highest reliability compared to the other parameters. In the study by Jemt [70], the discolouration of the soft tissue above the restoration as well as visible titanium margins were identified as present or not present. Such a dichotomous scale is feasible, but it may lead to a loss of efficiency [75].

The evaluation of the mesial and distal papilla in the present study was based on the papilla index score introduced by Jemt [70] as a simple clinical technique to assess recession or regeneration of the interproximal soft tissue. However, the scores were reduced to four and turned around to match the other aesthetic scores in the Copenhagen Index Score. In accordance with the present study, Jemt [70] found a relatively good reproducibility of the papilla index score. The measurements of the distal papilla score in study II were slightly less reliable than the measurements of the mesial papilla score. This result could be related to practical limitations to reproduce the distal papilla by photographs in the premolar region, which was in accordance with the results reported by Fürhauser et al. (2005).

Validity of aesthetic parameters

The validity of the six aesthetic parameters was assessed in study II to evaluate the usefulness of these parameters to measure the aesthetic outcome of single-tooth implant restorations. The convergent validity of the parameters was analysed by using the VAS, which is the most frequently used interval scale for dental, dentofacial or facial aesthetics [78]. The simplicity in using a categorical scale and the definition of each score were the major advantages of using a categorical scale compared with an interval scale such as VAS [75]. Furthermore, calibration of different observers is more efficient using a categorical scale compared to an interval scale, which makes the categorical scale more feasible for clinical evaluations. Some of the recently developed categorical scales for assessing the aesthetic outcome of implant-supported restorations [59, 66, 70, 79, 80, 82] have also been tested for reproducibility, but the validity was not evaluated.

Professional-reported aesthetic outcome

Using the five aesthetic parameters in the current clinical studies demonstrated that only the colour match score varied at different restoration materials. A significantly superior colour match of the restorations with the all-ceramic crowns compared to those with the metal-ceramic crowns was observed. In another comparative study of ISSCs by Gallucci et al. [18], the colour and translucency of the all-ceramic and metal-ceramic crowns did not vary significantly, and the translucency of all crowns was lower than the natural neighbouring teeth; however, the number of included crowns in that study was very limited.

The morphology of the all-ceramic and the metal-ceramic crowns in our clinical studies was comparable, which is in agreement with findings by Gallucci et al. [18]. The width of the crowns, which was one of the subparameters of crown morphology score, had a significant influence on the assessment of this aesthetic parameter in the study IV. In the edentulous regions, where the mesio-distal distances were greater than the corresponded anatomic crown width of natural premolars [128], the morphology of crowns was generally less optimal. This was mainly observed, where the two adjacent missing teeth were replaced with only one implant, and where an ISSC replaced a retained primary second molar.

The zirconia abutments were primarily used to reduce the greyish discolouration of the marginal peri-implant mucosa. However, in our clinical studies as well as in the other clinical studies [17, 61], the zirconia and the metal abutments induced no significant differences in the colour of the marginal peri-implant mucosa. In an *in vitro* study by Jung et al. [14], it was suggested that in clinical situations with a mucosa thickness ≤ 2 mm, the titanium abutments in contrast to zirconia abutments may cause a change in colour of the peri-implant mucosa. In a recent clinical study by Bressan et al. [129], the change in the peri-implant mucosa colour was significantly less at the zirconia than at the titanium abutments, but the results were not depended on the mucosa thickness.

The height of the papilla in the present clinical studies as well as in the other clinical studies [17, 130] was similar at the titanium and the zirconia abutments. The papilla height increased during the current studies, which is consistent with the results of the other clinical studies [131, 132]. The gingival biotype [132] and the cervical dimension of the permanent healing abutments [133] are some of the factors that have been suggested to influence the dimension of the interproximal papilla.

Patient-reported outcome

In the present prospective study patients with tooth agenesis treated with ISSCs reported on very few oral health related problems three years after crown insertions, which is consistent with the results of the other studies [3, 134]. In the present clinical studies, the patients did generally not notice considerably differences in the aesthetic outcome of the all-ceramic compared to the metal-ceramic restorations. This finding agrees with the results reported in a study by Gallucci et al. [18].

In the current clinical studies as well as in other studies of ISSCs [3, 65, 73, 76, 87, 135], the patients and the clinicians had significantly different aesthetic views to the performed restorations, which emphasizes the importance of involving patients in treatment planning and evaluation.

CONCLUSION

- Fracture of the veneering ceramic appears to be the most frequent fracture mode of ISSCs. More cyclic loadings until veneering fracture was estimated with the metal-ceramic than the zirconia-based all-ceramic restorations (study I).
- The six aesthetic parameters included in the CIS had an overall substantial intra-observer and moderate inter-observer agreement. No significant correlation between the professional- and patient-reported aesthetic outcomes was observed (study II).
- Generally, minor marginal bone loss was observed at implants supported zirconia, titanium and gold alloy abutments. No differences in marginal bone loss were registered between sites with zirconia and titanium abutments after short-time follow-ups. The sites with angulated gold alloy abutments had more marginal bone loss than the sites with zirconia and titanium abutments. The health of the peri-implant soft tissue was not influenced by the abutment materials (study III & IV).
- More optimal marginal adaptation was achieved at metal-ceramic than at all-ceramic crowns. Loss of retention was the most frequent biomechanical complication, which was registered at metal-ceramic restorations mainly in the posterior regions. Only few fractures of veneering ceramic were registered (study III & IV).
- The professional-reported aesthetic outcome demonstrated that implant-supported all-ceramic crowns provided a better colour match than metal-ceramic crowns. The crown morphology was influenced by the mesio-distal distance in edentulous space (study IV), and the mucosal discolouration (study III) as well as the papilla level (study III & IV)

increased. However, the restoration materials had no impact on the crown morphology, mucosal discolouration and papilla index scores after short-time observations. The patients did generally not noticed aesthetic differences between all-ceramic and metal-ceramic restorations (study III & IV)

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