

From the Klinik für Zahnärztliche Prothetik, Propädeutik und Werkstoffkunde
(Director: Prof. Dr. M. Kern)
at the University Medical Center Schleswig-Holstein, Campus Kiel
at Christian-Albrechts-Universität zu Kiel – Kiel University

**Retention of Metallic and Non-Metallic Double Crown-Retained
Overdentures on Implants**

Dissertation
to acquire the doctoral degree in dentistry (Dr. med. dent.)
at the Faculty of Medicine
at Christian-Albrechts-Universität zu Kiel – Kiel University

presented by
Aya Elkabbany, M.Sc.
From Saudi Arabia
Kiel 2021

1st Reviewer: Prof. Dr. Matthias Kern

2nd Reviewer: Prof. Dr. Dr. Patrick Warnke

Date of oral examination: 24.05.2022

Approved for printing, Kiel:

Signed: Prof. Dr. Matthias Kern

(Chairperson of the Examination Committee)

Contents

- Abbreviations*.....**II**
- 1. Introduction**..... **1**
 - 1.1. Different attachment systems for implant-retained overdentures**..... **1**
 - 1.2. Factors affecting the retention of the attachments** **2**
 - 1.3. Double crown-retained overdentures**..... **4**
 - 1.4. Types of double crown systems**..... **4**
 - 1.5. Fabrication methods for the double crown systems** **6**
 - 1.6. Materials used for double crown systems** **6**
- 2. Aim of the study** **9**
- 3. Materials and Methods**..... **10**
 - 3.1. Study groups** **11**
 - 3.2. Fabrication of the abutments**..... **11**
 - 3.3. Fabrication of the secondary crowns** **15**
 - 3.4. Measurement of the retention force**..... **23**
 - 3.5. Thermo-mechanical dynamic loading**..... **25**
 - 3.6. Statistical analysis** **26**
- 4. Results** **27**
 - 4.1. Retention force** **27**
 - 4.2. Thermo-mechanical dynamic loading**..... **29**
- 5. Discussion** **31**
 - 5.1. Discussion of the methods**..... **31**
 - 5.2. Discussion of the results**..... **34**
- 6. Conclusion**..... **37**
- 7. Summary** **38**
- 8. Zusammenfassung** **40**
- 9. References** **42**
- 10. Acknowledgement** **46**
- 11. Dedication** **47**
- 12. Appendixes** **48**

Abbreviations

Abbreviation	Description
°C	Degree Celsius
µm	Micrometer (0.001 millimeter)
Bis-GMA	Bisphenol A-glycidyl methacrylate
CAD/CAM	Computer-aided design and computer-aided manufacturing
CoCr	Cobalt-chromium
g	Gram
KV	Cold-formed (kaltverformt)
min	Minute
ml	Milliliter
mm	Millimeter
MPa	Megapascal
N	Newton
Ncm	Newton centimeter
PEEK	Polyetheretherketone
PEKK	Polyetherketoneketone
POM	Polyoxymethelyene
PVC	Polyvinylchloride
SD	Standard deviation
sec	Second
Ti	Titanium
ZrO ₂	Zirconia

1. Introduction

Complete edentulism is a common global health problem. A complete denture was considered the classical treatment for full edentulism. Recently, there was a paradigm shift regarding the standard therapy for the lower edentulous jaw. Edentulism could be treated with different forms of rehabilitation including conventional complete dentures, implant-retained overdentures as well as implant-supported fixed dental prostheses. Using at least two implants to stabilize the lower denture was recommended in different studies (22, 41, 44). Mandibular implant-retained overdentures are generally considered the preferable choice as it has considerable advantages; probable reduction of the residual ridge resorption, enhanced stability and retention, and may lead to an additional benefit in the quality of life and patient's satisfaction (21, 41, 57).

A systematic review discussed implant-retained removable partial dentures and implant-supported fixed dental prostheses in edentulous jaws and concluded that the insertion of two implants for a removable overdenture in the mandible shows favorable results. However, it has to be noticed that four implants revealed a slightly better outcome and may provide more comfort for some patients, particularly, when loading of the soft tissue is not preferred (36).

1.1. Different attachment systems for implant-retained overdentures

There are various types of attachments available for the use with implant-retained overdentures, splinting the implants as bar-clip constructions, or not splinting the implants as ball and stud type attachments, magnet attachments, and attachments with telescopic or conical copings (18, 21, 31, 69). Generally, the design includes both male and female components, the male component is usually fixed to the implant and the corresponding female component is usually a part of the removable overdenture (3). The attachment systems can be distinct according to the used material combination as well as according to the retention-mechanism used for denture retention (3, 14, 18, 31, 69).

The anatomic state of the mandible plays a crucial role in selecting the most suitable type of attachment system. Bars or parallel-walled telescopic crowns are most

appropriate in case of advanced atrophy of the alveolar crest as the prosthesis stabilization is critical particularly with regard to horizontal forces (31). Magnet connectors are considered an accepted alternative in patients with mandibular sufficient bone quantity, however they may be inferior with regards to patient-reported retention satisfaction and chewing comfort despite their easy handling (49). Ball attachments are often used in case of a pointed jaw (v-shaped), which interferes with the needed tongue space for a bar construction. Moreover, mandibular jaw with large curvature (U-shaped) is suitable for placement of four implants and a connecting bar (44). Furthermore, when the implants are arranged in a diagonal shape, ball and magnet attachments represent an equal option to bar-splinted attachments in terms of soft- and hard-tissue response, however their use accounts for less technical complications and easier hygiene procedures (25, 48).

The number of used implants is determined according to the type of prosthesis and the choice of prosthetic design, and vice versa, the number of implants to be inserted in regards to the anatomic status would affect the choice of the type and the design of the used prosthesis. Moreover, size, curvature and shape of the ridges impose the implants allocation over the arch (44).

Other factors determine the selection of attachment includes patient's expectations, economic status, as well as the expected level of oral hygiene (74). Additionally, the dentist's/technician's experience and training together with the availability of maxillo-mandibular relations are relevant aspects determining the choice of connector (31).

1.2. Factors affecting the retention of the attachments

All attachment systems for overdentures are subjected to wear-related changes resulting in a reduction and/or loss of retention over time. The exact mechanism of wear that inflects the retentive force of the different attachment systems remains poorly understood. However, it is believed to be multifactorial involving material composition and its wear features, design, dimensions, and the mode of retention of the attachment systems (2).

Bar, ball, and magnets attachments were compared in a 5-year prospective randomized clinical trial, the bar group showed common reactivation of the overdenture clips. In contrast, the ball attachments frequently required tightening of the abutment screws; besides that, renewal of the O-rings and the O-ring-housing were mostly needed. As for the magnet attachments, they required frequent renewal of magnets due to wear and corrosion, furthermore, there was poor scoring for the patient-reported satisfaction regarding retention and chewing comfort (49). The retentive properties of stud attachments (locator) were found to be better than those of ball attachments in a laboratory study that compared both of them (53, 68).

High implant success rates and minor prosthodontic maintenance efforts regardless of retention modalities used were noticed in a 3-year prospective study investigating removable implant-supported mandibular overdentures rigidly retained by telescopic crowns or by milled bars on four implants, so that a stable denture retention was presented together with healthy peri-implant structure for both anchoring systems. The clinical decision to choose between both systems may be based on the advantages and disadvantages of each system. A higher plaque/calculus formation was noticed with the bar design, while, telescopic crown attachments showed less favorable handling properties (39).

A double crown system ensures a stable denture position, and the secondary splinting of four implants with telescope crowns may achieve a better transfer of retentive forces to the individual fixtures crowns compared to the primary splinting with rigid or jointed bar attachments (8).

1.3. Double crown-retained overdentures

Recent studies recommend the use of double crown-retained removable partial dentures with natural teeth and/or implants as abutments for prosthetic rehabilitation (77). Double crown attachments have the advantage of providing adequate retention with satisfactory mastication and improved phonetics. They also allow horizontal stability and prevent distal extension base dislodgement away from the alveolar ridge. In addition, they are used in geriatric patients as they can be easily inserted and removed. Despite of these advantages, telescopic-retained removable partial denture fabrication is time consuming, technically sensitive, costly and there is a possibility of losing retention over time due to the mechanical wear of the abutments and copings (19, 23, 28, 31-33, 47, 56, 70, 78).

The double crown design basically entails a primary coping (inner telescope), which is permanently cemented to the abutment tooth while an implant abutment can be milled and therefore acts as the primary coping. A secondary coping (outer crown), which is rigidly anchored in the removable denture and engages the primary coping to form a telescope retainer unit. The basic component for retention and stabilization of the outer part is provided through the primary coping. The secondary crown, being an integral part of the removable superstructure acts as its anchor with the rest of the dentition (42). The forces are transferred alongside the long axis of the abutment teeth/implants resulting in guidance, support, and protection from movements that might dislodge the removable partial denture (20, 27).

1.4. Types of double crown systems

The design of the double crown retainers includes broadly two basic principles; the first principal is the conventional concept of rigid positional relationship between the inner and outer components. Therefore, the construction of a primary coping is based on the cylindrical principle of the telescope. This particular design involves an inter-surface friction during the insertion and removal of the superstructure as the two parts engage and disengage together. The second approach considers some built-in movement or resiliency between the two parts of the structure (42).

According to the retention mechanism used, double crown removable dentures are classified into different types: telescopic parallel crowns, conical double crowns and double crowns with additional retention elements. Telescopic parallel crowns attain the retention mechanism based on the friction between parallel-milled surfaces, while conical double crowns exhibit retention when the secondary part is completely seated “wedging effect”. Extra retention could be achieved by additional retention elements e.g., Marburg double crown (12, 70, 73). Electroforming is an important technique which ensures efficient retention mechanism. There is an accurate fit of components resulting in a durable and reproducible retentive force, this could be attributed to the automatically created precise fit onto the primary coping. Hence, electroformed copings acquire their retention from hydraulic impact and adhesion capillarity (20, 72).

An accurate fit between the crowns is essential for reliable retention of the cylindrical crowns, this could make the fabrication technically challenging for the lab technician. Furthermore, the continuous friction between the inner and outer crowns can lead to a higher wear rate. Conical double crowns aim to overcome the drawbacks of the cylindrical crowns (42). Retention is achieved via wedging effect, the amount of this effect is a function of the convergence angle of the inner crown, the smaller the convergence angle, the greater the retentive force (27). Moreover, their retention depends on the seating space and the seating force between both crowns, which may be controlled by means of occlusal stops (63).

It is important to achieve an appropriate retentive force for a sound function of double crown overdentures, as too strong retention may damage the periodontium or implant connection during denture removal. Whereas, too weak retention can result in loss of retention during mastication. Furthermore, a stable retentive force should be maintained in spite of the consecutive removal and insertions, as well as the long-term wear. Therefore, to maintain a constant retentive force, standard conditions of tribology effects between the contact surfaces of primary and secondary crowns in addition to excellent fit should be achieved. Hence, advanced fabrication techniques and novel material combinations have been developed to try to maintain a durable retentive force (1, 26, 47, 55).

1.5. Fabrication methods for the double crown systems

Typically, double crown telescopes are manufactured by casting using the traditional lost wax technique, electroforming, or by the use of CAD/CAM technology. However, in addition to the fact that the retention force is fundamentally affected by the precision and optimal fit between the crowns, it is also believed, that different fabrication methods have an effect on the retention of double crown system. Nonetheless, the impact of fabrication method is also depending on the type of the material used along with the used fabrication technology (55).

Fabrication of double crowns using casting technique, particularly telescopic crowns, requires special technical skills and experience to achieve an adequate and precise frictional retention between the primary and the secondary crowns (28, 47). Casting-shrinkage, which may lead to fit problems, has been reported with casting techniques. On the contrary, fabrication of double crowns using electroforming technique expedites the exact fit of dental restorations as they are directly formed on duplicated dies, therefore no casting-shrinkage is reported with this technique. Moreover, the electroforming process enhances the marginal fit and requires no special technical skill (9, 28). The CAD/CAM technology was introduced as an alternative to the lost-wax method as the conventional metal processing technique. Nowadays, the accuracy of the CAD/CAM technology has significantly improved due to the advances of the measuring methods and processing software. Hence, the fabricated double crown copings using CAD/CAM technology have gained a fine and homogenous structure (63, 75).

1.6. Materials used for double crown systems

The retention of double crown-retained prostheses differs according to different crown tapers, heights, used materials and the friction between the axial walls of the inner and outer crowns (7, 15, 27, 52, 76). However, the retention might decrease over time due to wear between the materials (27), which could be an abrasive and/or adhesive wear. Abrasive wear occurs when a hard, rough surface slides across a softer surface. On the contrary, adhesive wear occurs when two bodies slide over each other or are

pressed into one another, which promotes material transfer between the two surfaces (35).

The wear of double crowns is a common problem, which may necessitate the renewal of the prosthesis (4, 10). The use of gold alloys has been regarded as the most reliable choice in constructing double crown restorations (24). This is attributed to the low coefficient of wear of gold alloy, which helps in maintaining adequate long-term retention of the prosthesis (7, 39). Laboratory studies found a higher retention force in an electroplated system compared to a cast one (4, 55). Unfortunately, due to the marked rise of the gold price, its clinical use is continuously declining. Additionally, the biocompatibility of gold might interfere with its combination with other metals in the oral cavity (43).

Clinicians and manufacturers are seeking less expensive, more esthetic and biocompatible alternatives that can provide similar accuracy and long-term retention for double crown-retained overdentures. Zirconia is a non-corrosive material, its color resembles the color of teeth, and it has superior biocompatibility compared to gold alloy. In this regard, Engels et al. concluded that the materials used for double crown systems exhibit a significant influence on their retention (20). Electroplated secondary copings on zirconia primary crowns showed better retention and less wear than combinations of gold/gold and titanium/titanium (3, 72). In a clinical study, the 3-year survival of zirconia/electroplated double crown retained removable prostheses was similar to cast cobalt-chromium/electroplated double crown retained removable prostheses (61).

Polyetheretherketone (PEEK) is a semi-crystalline thermoplastic polymer with good mechanical properties. The chemical structure of poly-aromatic ketones provides stability at high temperatures exceeding 300°C, easy processing, high stiffness, and chemical stability. Additionally, PEEK is resistant to radiation damage and compatible with many reinforcing agents such as glass or carbon fibers. PEEK-based dental polymers may provide a possibility for a novel line of metal-free crowns and implant abutments, and could be an alternative option for patients who have a titanium intolerance or allergy (40). PEEK implant abutments revealed comparable values of

biofilm formation compared to abutments made of zirconia or titanium (29). Therefore, the thermoplastic materials might be a proper alternative for the fabrication of the abutments and the framework of the double crown-retained overdentures (65).

PEEK was found to be a suitable material when used on zirconia crowns and revealed acceptable results in a study that investigated the retention load between ZrO₂ primary crowns and secondary PEEK crowns. PEEK crowns were fabricated by milling, pressed from PEEK pellets, or pressed from granular PEEK, with three different tapers 0°, 1° and 2° (45).

The alternative materials for double crowns include other metals such as base metal alloys and titanium. CoCr alloys are characterized by reasonable biocompatibility, mechanical stability and a rather low density which gives them a lower weight in the contrary to gold alloys. CoCr alloys were typically used for removable partial dentures as well as for both crowns and bridges, their use in double crown system fabrication seems also to be suitable (51). Titanium is a biocompatible economical material with good mechanical properties and low thermal conductivity, which represents a suitable alternative to gold alloys (75). An in-vitro study investigated the long-term effects on the retention of double crowns made from different combination materials; the inner and outer copings made of titanium showed retention force comparable to those made from gold alloys (7).

Nevertheless, reported allergies to some of these metals evoke the need for non-metallic replacements. Some patients showed sensitivity to nickel and to a lesser extent also to cobalt (11). Although titanium is a biocompatible metal, it may cause inflammatory reactions in approximately 0.6% of patients (17, 62). Non-metallic alternatives include zirconia, polyoxymethylene (POM), polyetheretherketone (PEEK) or polyetherketoneketone (PEKK). However, information on the retention durability for these alternative materials for double crowns is not available (71).

2. Aim of the study

The present study aimed at investigating the effects of the different material combinations as well as the number of insertion/removal cycles on the retention force of double crown-retained overdentures on implants to try to determine the best combination of the restorative materials with best durable retention.

The null hypothesis of the study was that neither different combinations of evaluated materials nor the number of insertion/separation cycles would affect the retention of double crown-retained overdentures.

3. Materials and Methods

The study was carried out on cylindrical bases made from polyvinylchloride (PVC) material (Richter, Kiel, Germany). Four implants, 12 mm in length, were arranged parallel to each other in an arch simulating the clinical condition of restoring an edentulous mandible, with 10 mm inter-implant space anteriorly and 35 mm arch width posteriorly. The fulcrum line between the anterior and the posterior implants was 10 mm. The prepared sites represented the mandibular inter-foraminal area at the lateral incisor and the first premolar positions. The implants were 3.5 mm in diameter for the lateral incisors, and 4 mm in diameter for the premolars (Sky Implants system, Demo implants, Bredent, Senden, Germany). To standardize the position of the implants for all specimens, a metal template was constructed (Figure 1). The implants were attached to the PVC bases using a BisGMA based temporary crown and bridge material (LuxaTemp, DMG, Hamburg, Germany). Retentive holes were prepared within the PVC bases using a round bur before inserting the BisGMA. The retentive holes were made in different angled levels to maintain the stability of the implants within the PVC bases during the test.

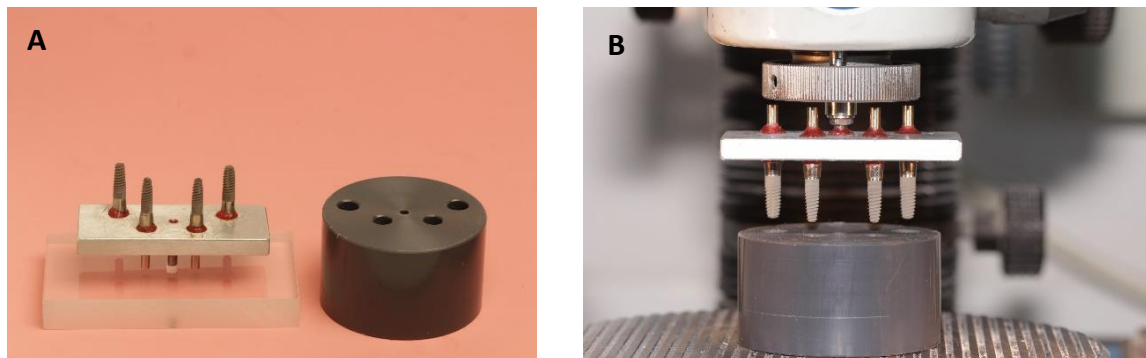


Figure 1. A: cylindrical base made from polyvinylchloride (PVC) and four implants fixed to the metal template. B: Insertion of the implants in the PVC-base using the milling machine.

3.1. Study groups

Five different groups of eight specimens each were constructed (Table 1). Group ZP; zirconia (3Y-TZP) abutments (KATANA Zirconia, HT High Translucent, Kuraray Noritake Dental, Tokyo, Japan, LOT DMZHE)/PEEK framework (BioHPP for2press, Bredent, Senden, Germany, LOT 439061). Group PP; PEEK abutments (breCAM.BioHPP, Bredent, LOT 439876)/PEEK framework. Group TP; titanium (grade 4 KV) abutments (SKY prefab titanium, Bredent, LOT 445342)/PEEK framework. Group TC; titanium (grade 4 KV) abutments/CoCr alloy framework (Tizian Blank NEM 98 mm, Schütz Dental GmbH, Rosbach, Germany). In the control group TG, the abutments were constructed from titanium (grade 4 KV) and the outer copings were electroformed with pure gold copings (Gramm GES Electroforming System, GAMMAT optimo2, Gramm Technik, Ditzingen-Heimerdingen, Germany) and bonded to cast CoCr framework (WIRONIUM, Bego, Bremen, Germany).

Table1. Different material combinations of the study groups.

Type	Test groups				Control group
	Group ZP	Group PP	Group TP	Group TC	Group TG
	N=8	N=8	N=8	N=8	N=8
Abutment material	Zirconia	PEEK	Ti	Ti	Ti
Outer coping material	PEEK	PEEK	PEEK	CoCr	Gold electroformed/bonded to a CoCr framework

N: number of specimens

3.2. Fabrication of the abutments

To standardize the dimensions of the abutments (primary copings), they were designed and manufactured with CAD-software (Dental Designer-Premium 2013, 3Shape, Copenhagen, Denmark)/CAM system (Zenotec select hybrid, Wieland Dental + Technik, Pforzheim, Germany) (Figure 2).



Figure 2. Designing of the abutments using the CAD-software.

The abutments were designed as conical crowns with 1° taper. The length of the abutments was 7 mm with an average retention height of 4 mm, while the width of the finish line was 0.8 mm (Figure 3). Subsequently, they were milled from zirconia, titanium (grade 4 KV), and PEEK materials. Additionally, the zirconia abutments were sintered according to the manufacturer's instructions.

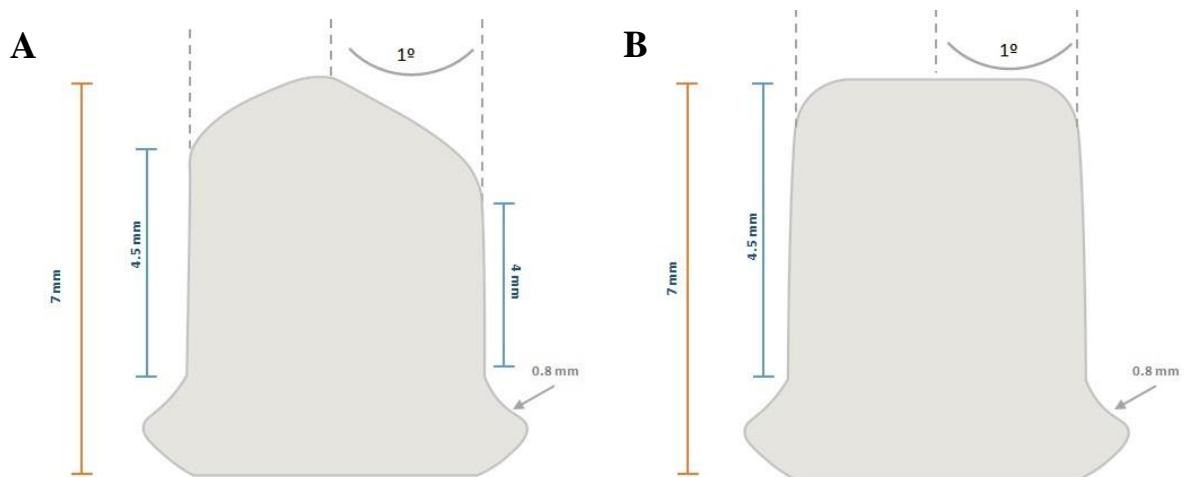


Figure 3. Diagram representing the dimensions of the abutments; A: Anterior abutment; B: Posterior abutment.

The milled titanium abutments were aligned directly to the implants and tightened at a torque of 25 Ncm. Ti-bases were aligned onto the implants and tightened at a torque of 25 Ncm (SKY uni.fit CAD abutment incl. screw, Bredent, LOT 443385). Ti-bases and the inner surfaces of the zirconia and PEEK abutments were steam-cleaned and air-abraded using 110 μ m alumina particles at pressure 2.5 bar for both Ti-bases and PEEK abutments, and 50 μ m alumina particles at pressure 1 bar for zirconia abutments (Figure 4-A, B). This was followed by ultrasonic cleaning in 99% isopropanol for 3 minutes. Subsequently, zirconia and PEEK abutments were cemented to the Ti-bases according to the manufacturer's instructions using dual-cure composite adhesive cement (DTK adhesive, Bredent, LOT 440430) (Figure 4-C), after applying a primer layer (MKZ-Primer, Bredent, LOT 201160) for conditioning both the zirconia and the titanium using a disposable brush and let dry for 30 seconds. The PEEK abutments were conditioned using the PEEK specific primer (Visio.link, Bredent, LOT 154931) and polymerized for 90 seconds using a light polymerization unit (Heraflash, Heraeus Kulzer, Germany).



Figure 4. A: Ti-base after air abrasion and its screw. B: Inner surface of zirconia abutment during air abrasion. C: DTK adhesive, MKZ primer, and Visio.link primer

A set of 1° zirconia finishing burs (Komet Dental, Lemgo, Germany) was used to finish the zirconia abutments using the milling unit with a water turbine (Presto Aqua II, NSK dental, Tochigi, Japan) and polished by using diamond paste and brushes (Figure 5). Regarding the PEEK and the titanium abutments, a set of 1° Tungsten Carbide burs for fine milling and ultra-fine milling (Komet Dental) were used with the milling unit. Milling oil was used only when milling the titanium abutments (Figure 6). All surfaces were then finished using silicon polishers, polishing brushes and pastes according to the manufacturer's instructions (Figure 7).

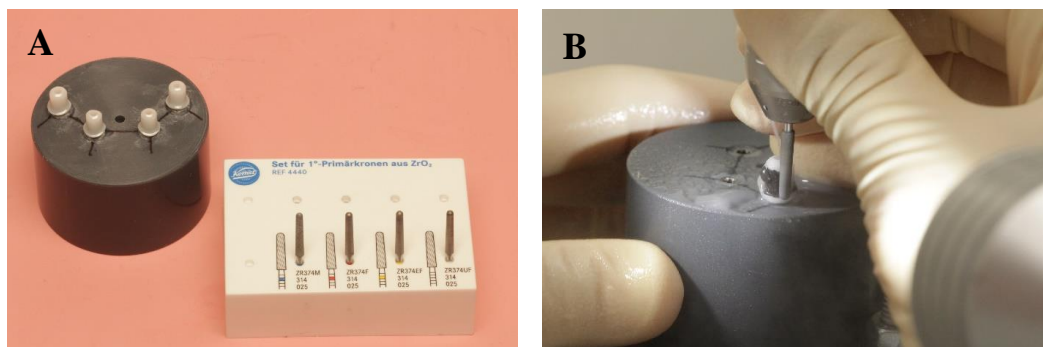


Figure 5. A: Zirconia finishing burs. B: Finishing of the zirconia abutments using the milling unit with a water turbine.

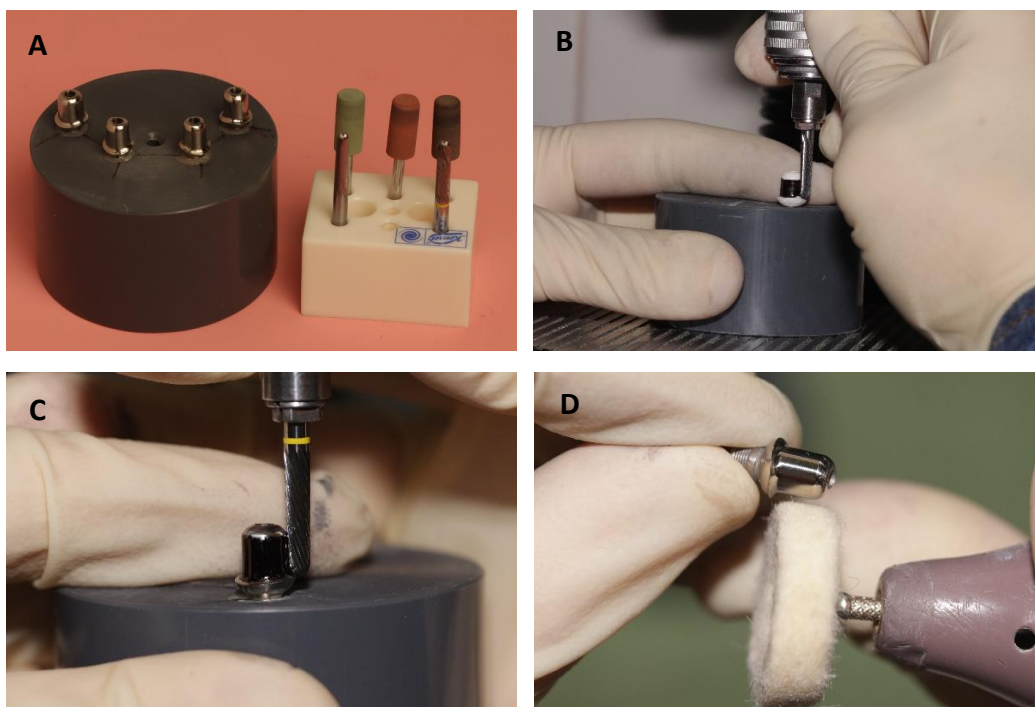


Figure 6. A: Ti abutments and Tungsten Carbide burs for finishing Ti and PEEK abutments; B: Finishing of the PEEK abutments using the milling unit; C: Finishing of the Ti abutments using the milling unit; D: Polishing the Ti abutment with brushes.

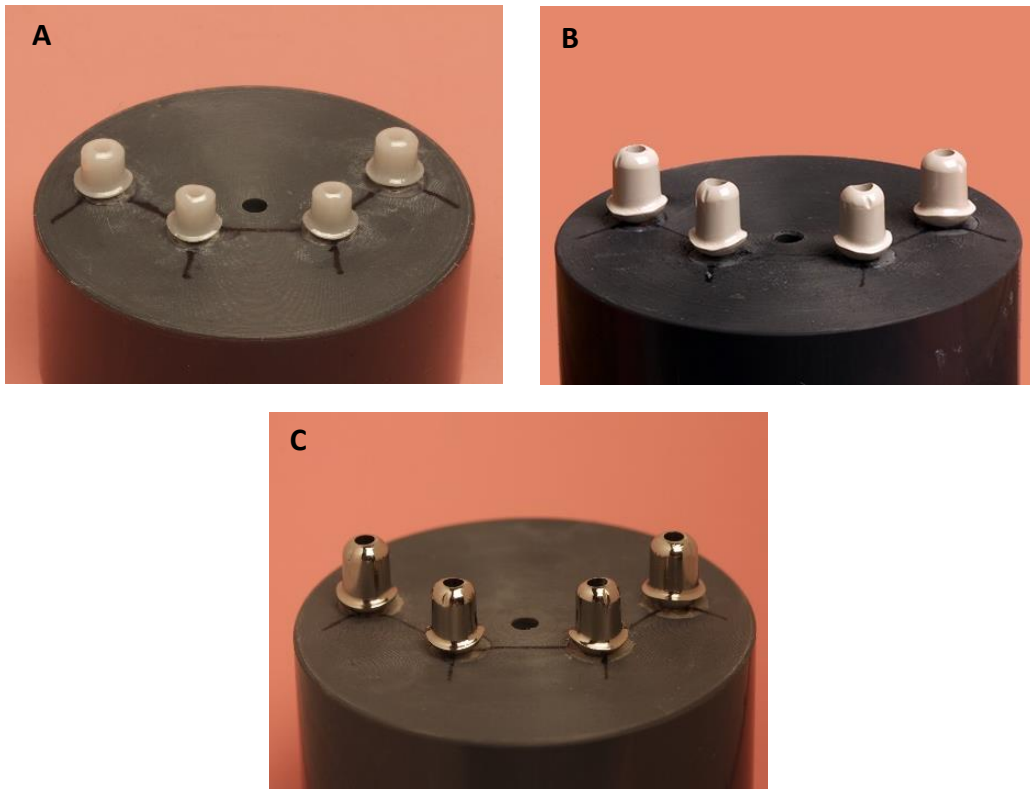


Figure 7. Finished abutments; A: Zirconia, B: PEEK, C: Titanium

3.3. Fabrication of the secondary crowns

The secondary copings of the test groups from the PEEK material were waxed over the abutments directly as a framework with a thickness of 0.8 mm. Sprues of 2.5 mm diameter were used to connect the coping's middle portions. While sprues of 4 mm diameter were used to connect the top of the copings to a loop at the meeting middle point of the top sprues to allow the fixation in the testing machine (Sprue channel, Bredent) (Figure 8). Subsequently, the waxed frameworks were invested and injected using the For2Pressmachine (Bredent) with the ceramic reinforced PEEK (Bio HPP, Bredent) according to the manufacturer's instructions.

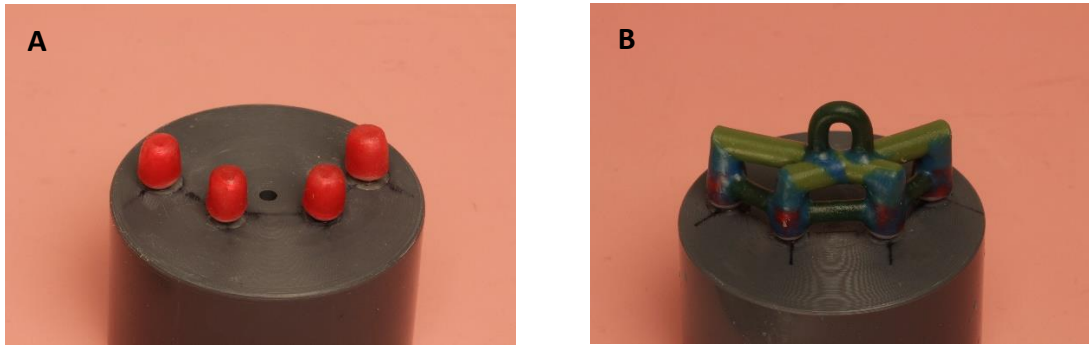


Figure 8. A: The secondary copings waxed over the abutments; B: The waxed framework.

The frameworks were removed from the abutments and fixed into size-9 investment molds (for2press mold set metal ring, Bredent) (Figure 9-A). The investment material was mixed with 100% liquid concentration. For the size-9 mold, 450g powder (Brevest for2press, Bredent, LOT 163206) was mixed with 106 ml liquid (Bresol for2press, Bredent, LOT 070616) (Figure 9-B, C). After twenty-five minutes, allowing setting of the investment, the ring was placed in the furnace together with the press plunger (for2press filler, Bredent, LOT 438195) (Figure 10-A). The furnace temperature was allowed to raise to 850 °C and then maintained for sixty minutes, afterward, the temperature was cooled down to 400 °C, with a cooling speed of 5 °C/min, and held for another 60 min. The melt reservoir of the ring was then filled with one pellet of 15 g of BioHPP and kept in the furnace for additional twenty minutes at 400 °C. The mold containing the melted BioHPP and the plunger on top was immediately transferred into the pressing unit (for2press unit, Bredent, Germany) and pressed using five bars pressure under vacuum for five minutes, then without vacuum for forty minutes until cooling down (Figure 10-B).

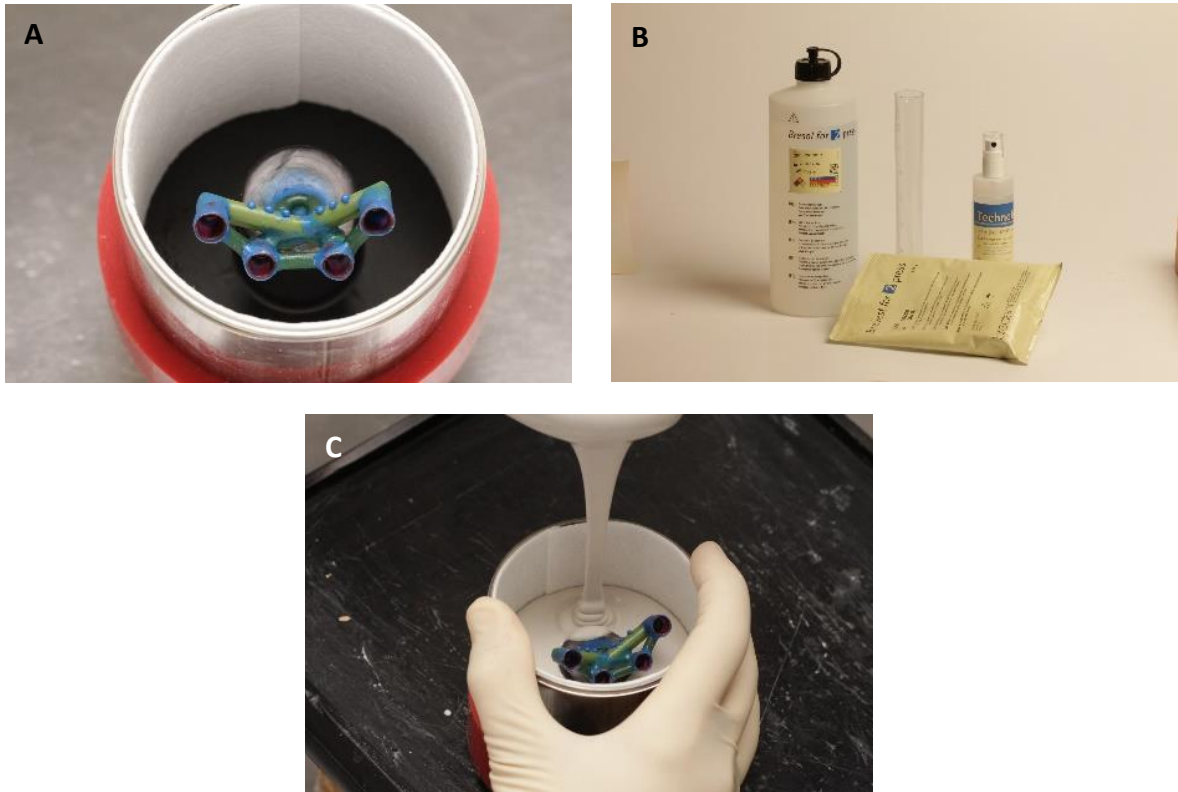


Figure 9. A: The framework fixed in the investment mold; B: The investment material; C: The investment material poured into the mold.

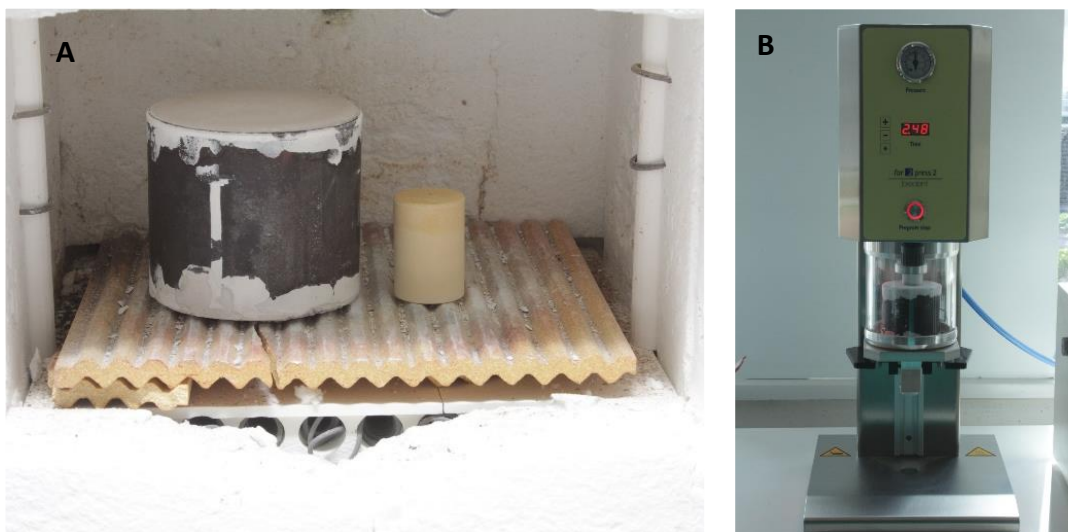


Figure 10. A: The ring and the press plunger placed in the furnace; B: The pressing unit.

The pressed frameworks were devested and the remaining investment material was removed by air-abrasion with 110 μm alumina particles at 2.5 bar pressure. Thereafter, the frameworks were adapted to their corresponding abutment-model and finished using crosscut burs (Figure 11).

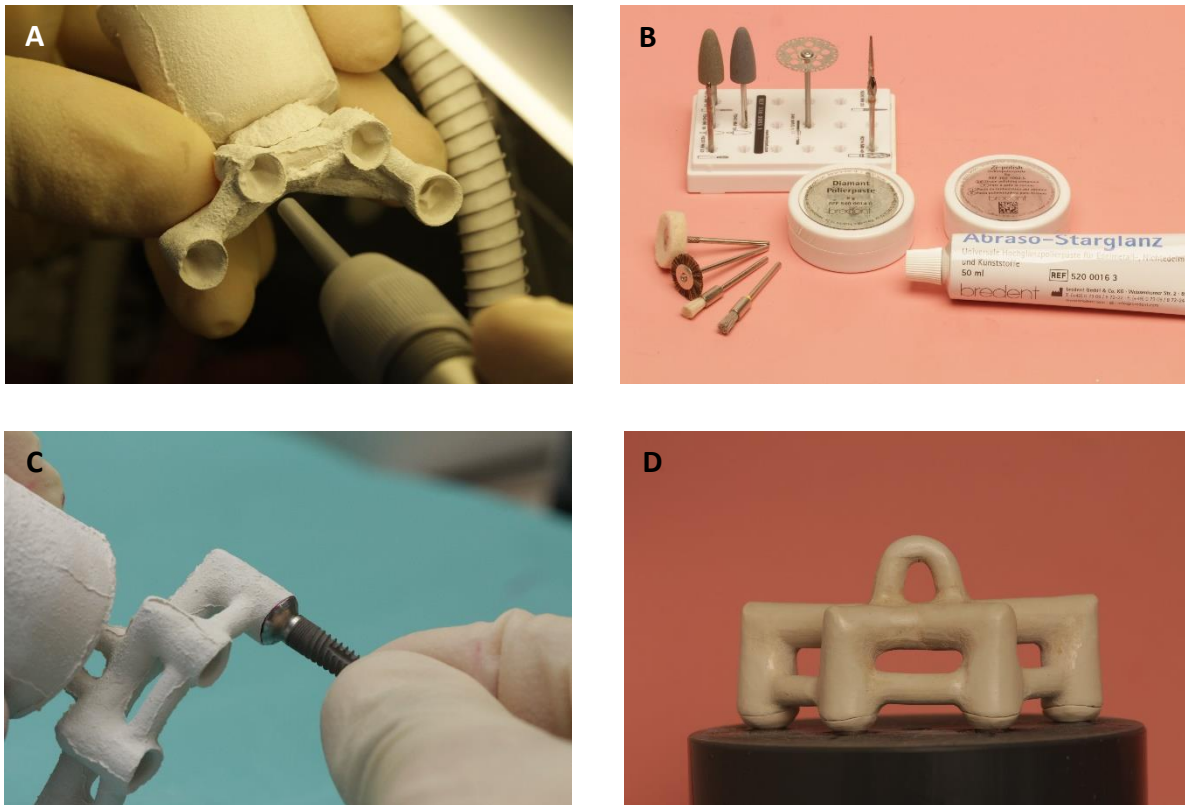


Figure 11. Steps of finishing the PEEK framework; A: Framework being air-abraded; B: Finishing crosscut burs and polishing pastes; C: The framework adapted to the abutment; D: Finished PEEK framework.

A universal testing machine (Zwick Z010, Zwick GmbH, Ulm, Germany) was used to measure the retention of the PEEK frameworks for each specimen in all groups, in order to ensure that the initial retention value of the eight samples in each group would be within a close range to each other.

The CoCr frameworks (Tizian Blank NEM 98 mm, Mani Schütz Dental) were designed similar to the PEEK frameworks and manufactured using CAD/CAM technology. The abutments were scanned using a tactile scanner (Renishaw Scanner DS 10, Schütz Dental GmbH) (Figure 12).



Figure 12. CoCr framework.

The secondary copings of the control group were electroformed from pure gold over the titanium abutments directly. Initially, the abutments were attached to copper rods with pattern resin (Pattern Resin LS, Alsip, IL, USA) (Figure 13-A). Likewise, the screw canals were filled with resin to avoid ditching the electroformed gold into the canals. Afterward, the abutments were spray-coated with a homogenous thin layer of silver lacquer (Silver lacquer airbrush, Gramm Technik, Ditzingen-Heimerdingen, Germany) (Figure 13-B). The prepared abutments were then placed in a fully automated electroforming system (GES, Gramm Technik) to form a 0.25 mm thick galvanic gold layer (Figure 13-C). The electrolyte (Ecolyt SG200, Gramm Technik, LOT 20170419), the activator (Activator SC200-T, Gramm Technik, LOT 20170214) and the chip card GES for gold electroforming were used as stated in the manufacturer's manual (Figure 13-D). Ultimately, the electroformed copings were separated from the corresponding abutments. The silver layer on the surface was finally removed by 53% nitric acid. No further adjustment of the retention force was performed (Figure 13-E).



Figure 13. Fabricating the secondary copings of the control group; A: The abutments were attached to the copper rods with pattern resin. B: The abutment spray-coated with silver lacquer. C: The abutments coated with electroformed gold layer. D: The electrolyte (Ecolyt SG200)) and the activator (Activator SC200-T). E: Final Secondary gold copings.

The cast CoCr frameworks (Wironium) were fabricated according to the same design of the PEEK frameworks to support the electroformed gold copings. Approximately 0.1 mm space was permitted between the frameworks and the copings to allow the passive fit and to accommodate the adhesive luting resin. The copings were coated with the relief-wax to permit the aforementioned space (Figure 14-A). The models were then duplicated using the duplicating silicone (Technosil A+B, Bredent, LOT 439654, LOT 433215) (Figure 14-B). The investment material (Wirofine, BEGO, Germany) was mixed by vacuum machine following the manufacture instructions then poured into the molds in small increments over the vibrating machine (Figure 14-C). The investment was left to set for sixty minutes then the frameworks design was waxed directly over the investment casts (Figure 14-D, E). The investment casts were secured on the bottom of the ring-mold-former and was gradually filled with the investment material over the vibrating machine. After casting the metal, the rings were devested and the remaining investment material was removed from the frameworks by air-abrasion with 110 μm alumina particles at 2.5 bar pressure (Figure 14-F).

The secondary copings were bonded to the framework with the DTK-adhesive following the manufacturer`s instructions. The gold copings were silica-coated with Rocatec Soft at 2.8 bar pressure, cleaned with compressed air for 15 seconds then conditioned using a 1:1 mix of the MKZ Primer and the activator (MKZ EM-Activator, Bredent, LOT 201161) and left to dry for 30 seconds (Figure 15-A, B). Whereas, the CoCr frameworks were conditioned using the MKZ Primer after air-abrasion with 110 μm alumina particles at 2.5 bar pressure. The framework was then filled with the DTK-adhesive and seated over the gold copings (Figure 15-C, D).

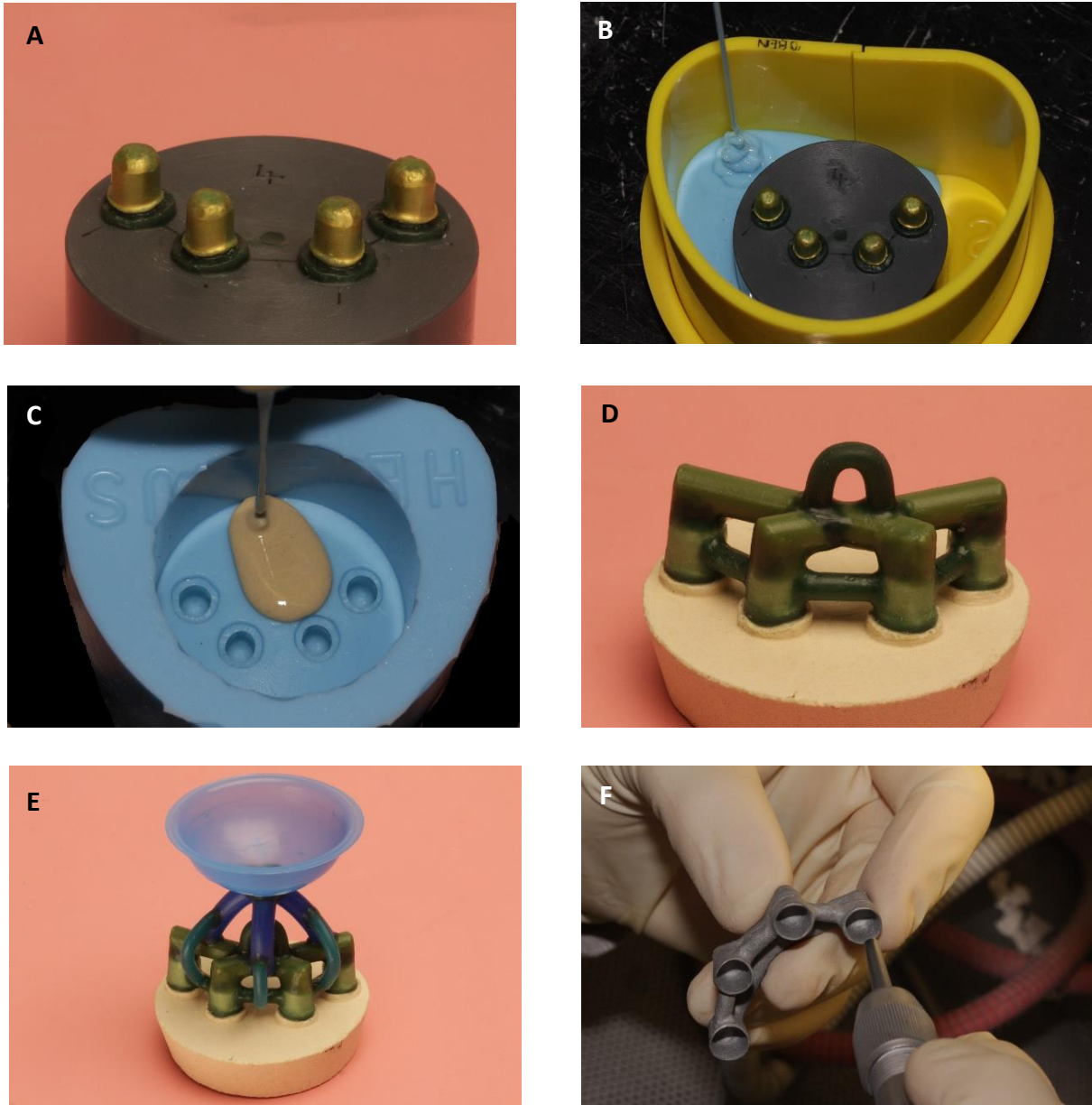


Figure 14. Fabricating of the CoCr framework; A: The abutments coated with the relief-wax; B: Duplicating the model with silicone; C: The investment material poured into the silicone mold; D, E: The frameworks design waxed over the investment cast; F: Air-abrasion of the cast metal framework with 110 μ m alumina particles at 2.5 bar pressure.

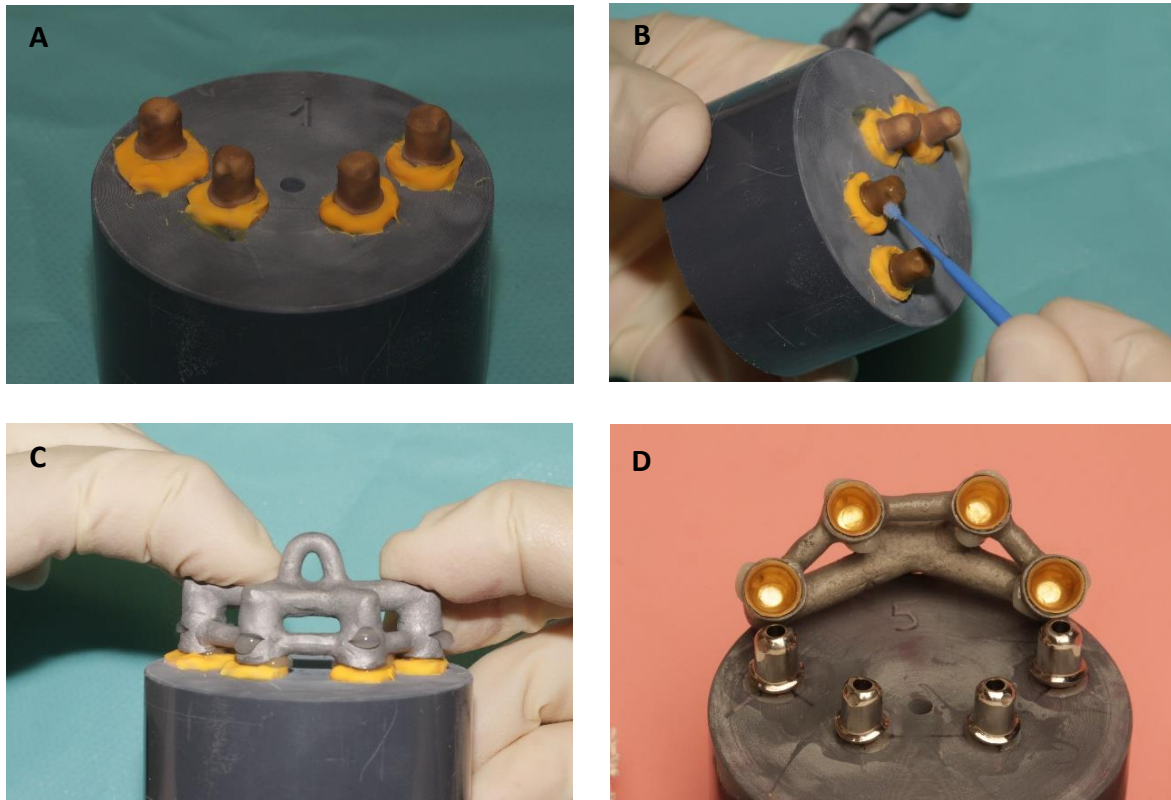


Figure 15. Bonding the gold copings to the framework. A: The gold copings after air-abrasion; B: The gold conditioned using a 1:1 mix of the MKZ Primer and the activator; C: The CoCr frameworks being seated over the gold copings; D: Finished model of the control group (group TG).

3.4. Measurement of the retention force

In a chewing simulator device (SD Mechatronik, Feldkirchen-Westerham, Germany), all specimens were subjected to 10,000 insertion/separation cycles, which corresponded to approximately 10 years of removing and inserting the denture three times daily. During the test, the specimens were immersed under de-ionized water at room temperature ($20\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$) to simulate the moist intraoral conditions, and to ensure the removal of wear rests from the friction area. A speed of 7 mm/sec was used in the present study at an axial load of 98 N to ensure the complete seating of the overdentures frameworks on their corresponding abutment models. The direction of the dislodging force was adjusted parallel to the path of insertion. For each separation cycle, the

maximum retention force value was recorded in N, using force transducers (Typ U9C, Hottinger Baldwin Messtechnik, Darmstadt, Germany) and the recording software (DIAdem, GFS Systemtechnik, Aachen, Germany) (Figure 16).

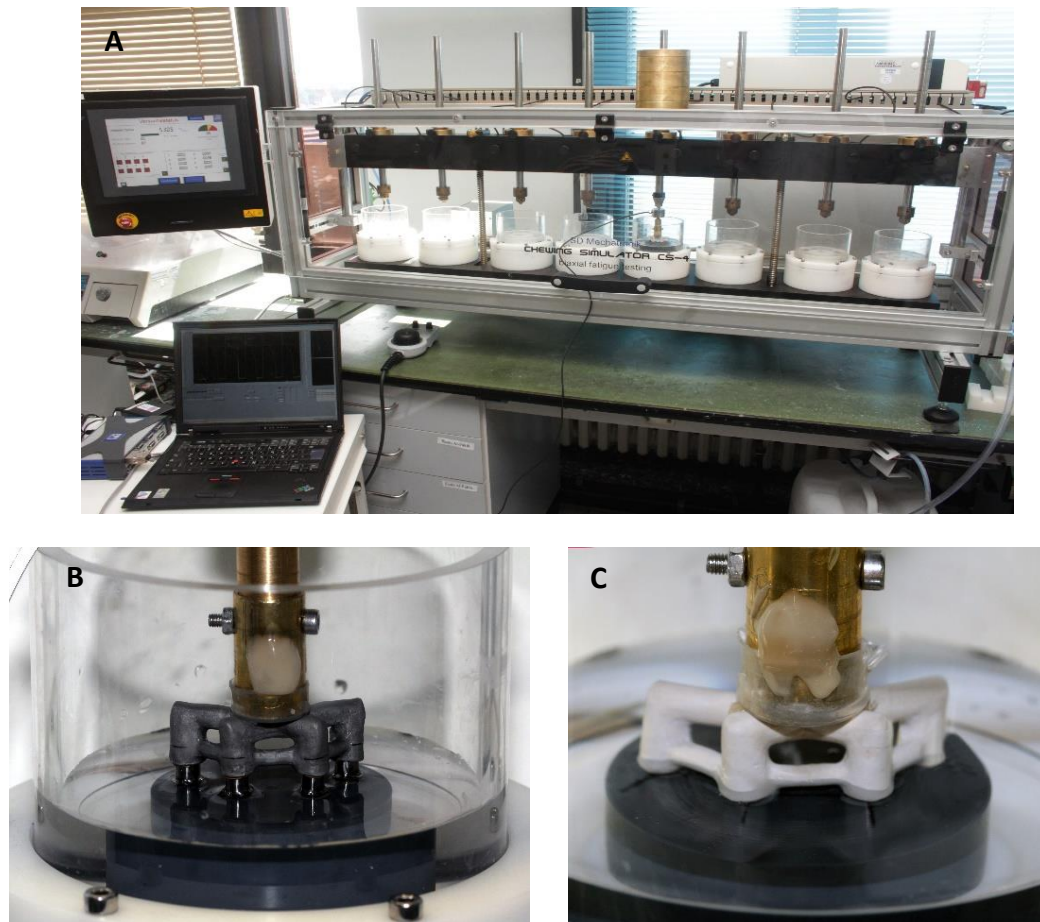


Figure 16. A: The chewing simulator device; B: A specimen of the TG group during separation; C: A specimen of the PP group during insertion.

The data was tabulated and statistically analyzed after 0, 100, 200, 300, 400, 500, 1,000, 2,000, 3,000, 5,000, 8,000, 10,000 cycles and the retention forces of the specimens were analyzed. For each interval, five surrounding measurements were used to calculate the mean value, which represented the mean retention at the corresponding test interval.

3.5. Thermo-mechanical dynamic loading

After finishing 10,000 insertion/separation cycles on the chewing simulator device, the same specimens were then tested for the thermo-mechanical dynamic loading. Chewing load simulation was transferred to the mandible through an acrylic base (Aesthetic Autopolymerisat, Candulor, Zürich, Switzerland), which was constructed over the frameworks extending posteriorly to the molars area. The loading point was the intersecting expected point between the extended line between the right and the left first molars and the medial line (34). A screw was used to receive the chewing load; 0.5 mm was permitted between the bottom of the screw and the metal top fixed into the PVC base. This space simulated the resilience of the residual ridge tissues (Figure 17).

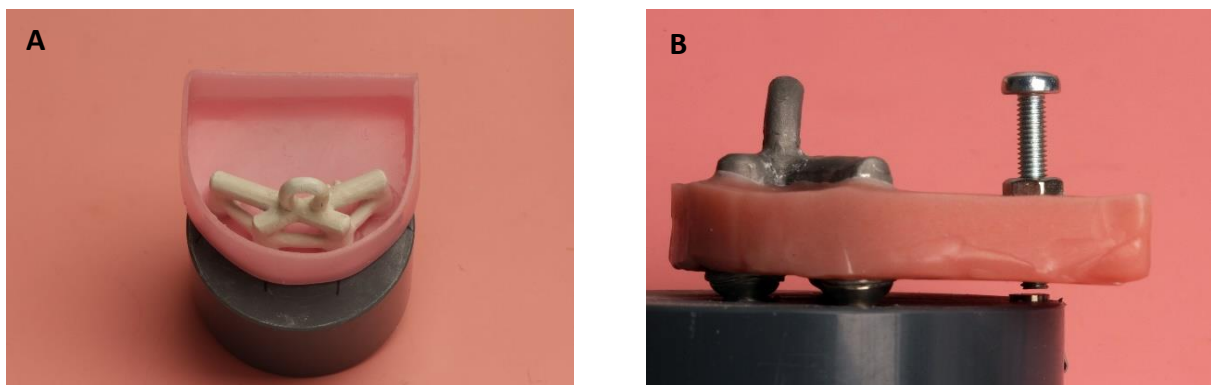


Figure 17. A: Wax preparation for pouring the acrylic base; B: A 0.5 mm distance between the bottom of the screw and the metal top fixed into the PVC base.

In the chewing simulator device, all the specimens were subjected to 1,200,000 chewing cycles, which corresponded approximately to five years' service-time. Sixty Newton vertical load was applied on the loading point at a speed of 30mm/sec. In addition to the cyclic loading, thermo-cycling was applied with a temperature ranging between 5 °C and 55 °C (Figure 18-A). To identify the change in retention, the retentive force of each specimen was measured using the universal testing machine 10 times before and after the chewing test while immersed in water. The retentive force of each specimen was measured with a speed of 8 mm/sec after it had been fitted with 50 N axial

loading (Figure 18-B). Group TC was excluded from this test due to technical difficulties of measuring the retention using the universal testing machine.

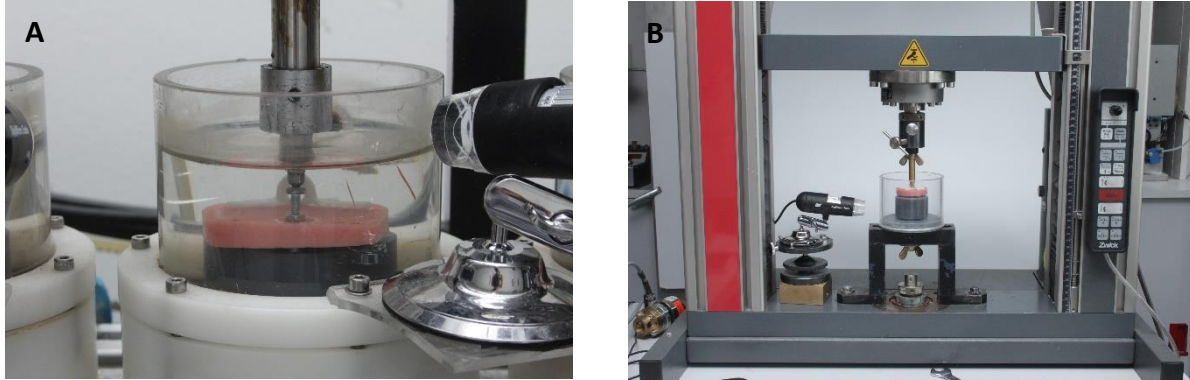


Figure 18. A: A model fixed in the chewing simulator device; B; A model fixed in the universal testing machine.

3.6. Statistical analysis

Results were reported as medians and means with standard deviations (SD). Normal distribution of the data was tested by the Shapiro-Wilk test. The non-parametric Friedman test and Dunn-Bonferroni post-hoc test were performed to compare the median values of retention at different cycles within each test group. Levene test was used to assess the equality of variances among the test groups. Moreover, one-way ANOVA and a Games-Howell post-hoc test were used to compare retention forces between the test groups at different cycles. Paired T-test was used to compare the retention force before and after the dynamic loading test within each group. Statistical significance level was established at $p \leq 0.05$. Statistical analyses were performed using IBM SPSS Statistics for Windows, Version 22.0 (IBM Corp. Armonk, NY, USA).

4. Results

4.1. Retention force

The retention forces of all test groups at different time intervals are shown in Table 2. The initial median retention of all groups ranged from 10.0 to 33.3 N. After 10,000 insertion/separation cycles, the median retention ranged from 10.3 to 35.0 N. The Shapiro-Wilk tests indicated no violation of the assumption of normality for 95% of comparisons within the tested groups at different cycles intervals; only 5% (3 comparisons out of 60) were not normally distributed.

According to the Friedman test, the change in the retention forces after 10,000 insertion/separation cycles was not statistically significant within ZP and TG groups ($p>0.05$). However, within groups PP and TP there was a slight increase in retention, which was partially significant after the first 1,000 cycles ($p\leq 0.05$). Only within group TC, the retention showed fluctuation at the beginning followed by with partially significant continuous decrease of retention. The change in the retention of all groups over 10,000 insertion/separation cycles is illustrated in Figure 19.

Pairwise comparison using Dunn-Bonferroni post-hoc test revealed a significant increase in retention for group PP after 1,000, 2,000, 3,000, and 8,000 cycles. For group TP, there was a significant increase after 500 and 1,000 cycles. Moreover, within group TC, there was a difference between the decreased retention after both 8,000 and 10,000 cycles versus the increased retention after 200 and 1,000 cycles.

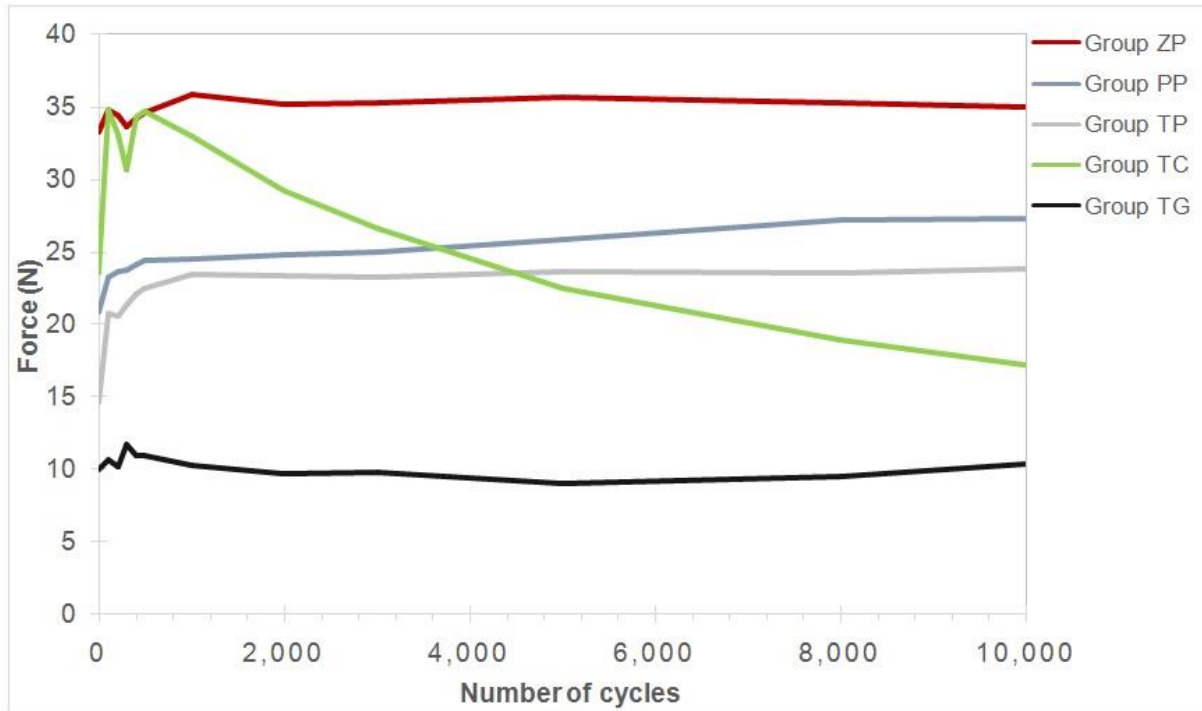


Figure 19. The median retention of all groups over 10,000 insertion/separation cycles. Group codes see Table 1, page 15.

Levene test showed inhomogeneity of variances among the test groups at different measuring cycles. One-way ANOVA test showed significant differences in the retention force when comparing all test groups at different cycles; Table 2 summarizes the results of the non-parametric Games-Howell post-hoc test. Hence, the median retention force of group ZP was significantly higher than that of groups PP, TP and TG. There was no statistically significant difference between groups PP and TP. Group TG had significantly lower retention than the other groups except when compared to group TC after high cycle numbers and to groups PP and TP initially. Group TC showed high fluctuation and therefore almost no difference to other groups except to group TG after a low number of cycles.

Table 2: Medians, means, and standard deviations of prosthesis retention in Newton after different insertion/separation cycles for all groups. Statistically different medians ($p \leq 0.05$) are indicated by different lower-case letters (within a column for the same group according to the Dunn-Bonferroni post-hoc test) or by different upper-case letters (within a row for the same number of cycles according to the Games-Howell post-hoc test).

Cycles	ZP		PP		TP		TC		TG	
	Median	Mean (\pm SD)	Median	Mean (\pm SD)	Median	Mean (\pm SD)	Median	Mean (\pm SD)	Median	Mean (\pm SD)
0	33.3 a, A	33.1 (6.7)	20.8 b, B	21.5 (4.1)	14.6 c, B	14.5 (5.7)	23.5 ab, AB	24.4 (10.0)	10.0 a, B	11.0 (8.4)
100	34.8 a, A	34.3 (6.1)	23.3 ab, B	24.6 (5.2)	20.7 bc, BC	22.1 (6.7)	34.8 ab, AB	32.3 (12.0)	10.6 a, C	10.9 (8.0)
200	34.4 a, A	33.7 (4.5)	23.6 ab, B	25.2 (5.0)	20.5 abc, B	22.8 (7.0)	33.0 a, AB	36.3 (11.7)	10.2 a, C	10.7 (8.3)
300	33.7 a, A	33.2 (4.1)	23.7 ab, B	25.6 (5.1)	21.3 abc, B	23.5 (6.7)	30.6 a, AB	37.5 (16.1)	11.7 a, C	10.8 (8.0)
400	34.2 a, A	33.5 (4.0)	24.1 ab, B	25.8 (5.0)	22 abc, B	24.0 (6.7)	34.3 a, AB	37.3 (14.3)	10.9 a, C	10.6 (8.0)
500	34.6 a, A	34.0 (3.9)	24.4 ab, B	25.4 (3.7)	22.4 ab, B	24.3 (6.7)	34.7 a, AB	37.9 (13.8)	10.9 a, C	10.5 (8.1)
1,000	35.9 a, A	34.6 (4.1)	24.5 a, B	26.2 (4.8)	23.4 ab, B	26.4 (5.9)	33 a, AB	35.7 (13.5)	10.3 a, C	10.5 (8.4)
2,000	35.1 a, A	35.6 (6.1)	24.8 a, B	26.6 (5.2)	23.4 ab, B	25.2 (6.5)	29.2 ab, AB	32.3 (11.2)	9.7 a, C	10.4 (8.8)
3,000	35.3 a, A	35.8 (7.1)	24.9 a, AB	26.7 (5.2)	23.2 ab, B	25.3 (6.4)	26.6 ab, AB	29.7 (11.1)	9.7 a, C	10.6 (8.8)
5,000	35.6 a, A	35.9 (7.4)	25.8 ab, B	26.2 (4.0)	23.6 ab, AB	25.4 (6.3)	22.5 ab, ABC	25.8 (10.8)	9.0 a, C	10.7 (8.9)
8,000	35.2 a, A	35.3 (6.4)	27.2 a, B	26.6 (3.1)	23.5 ab, B	25.3 (6.0)	18.9 b, ABC	21.2 (10.7)	9.4 a, C	11.3 (9.5)
10,000	35.0 a, A	35.2 (6.1)	27.3 ab, B	26.6 (3.6)	23.8 a, B	25.5 (5.9)	17.2 b, BC	19.7 (8.9)	10.3 a, C	11.6 (9.6)

SD: standard deviation

4.2. Thermo-mechanical dynamic loading

The results of the retention force before and after applying 1,200,000 chewing simulation cycles are summarized in Table 3 and Figure 20. The Shapiro-Wilk tests indicated no violation of the assumption of normality. The mean retentive force in N of group PP was 13.2 N (± 3.3) before performing the chewing test and 12.2 N (± 3.4) afterwards. Regarding group TG, the mean retentive force was 7.1 N (± 3.6) and 9.6 N (± 6.1), respectively. There was no statistically significant change in the retentive force ($p > 0.05$) in group PP and group TG. Unlike, there was a statistically significant change

in the retentive force in groups ZP and TP, before and after the chewing test, as it slightly increased from 13.2 N (± 4.6) to 16.4 N (± 6.1) in group ZP ($p=0.002$), while in group TP, the mean retentive force decreased minimally from 4.9 N (± 2.1) to 3.3 N (± 1.7) after the chewing test ($p=0.046$).

Table 3: Results of the retention force in N before and after performing the **thermo-mechanical dynamic** loading

	Mean retentive force in N (\pm SD)			
	ZP	PP	TP	TG
Before the thermo-mechanical dynamic loading	13.2 (± 4.6)	13.2 (± 3.3)	4.9 (± 2.1)	7.1 (± 3.6)
After the thermo-mechanical dynamic loading	16.4 (± 6.1)	12.2 (± 3.4)	3.3 (± 1.7)	9.6 (± 6.1)
<i>p value</i>	0.002	0.361	0.046	0.111

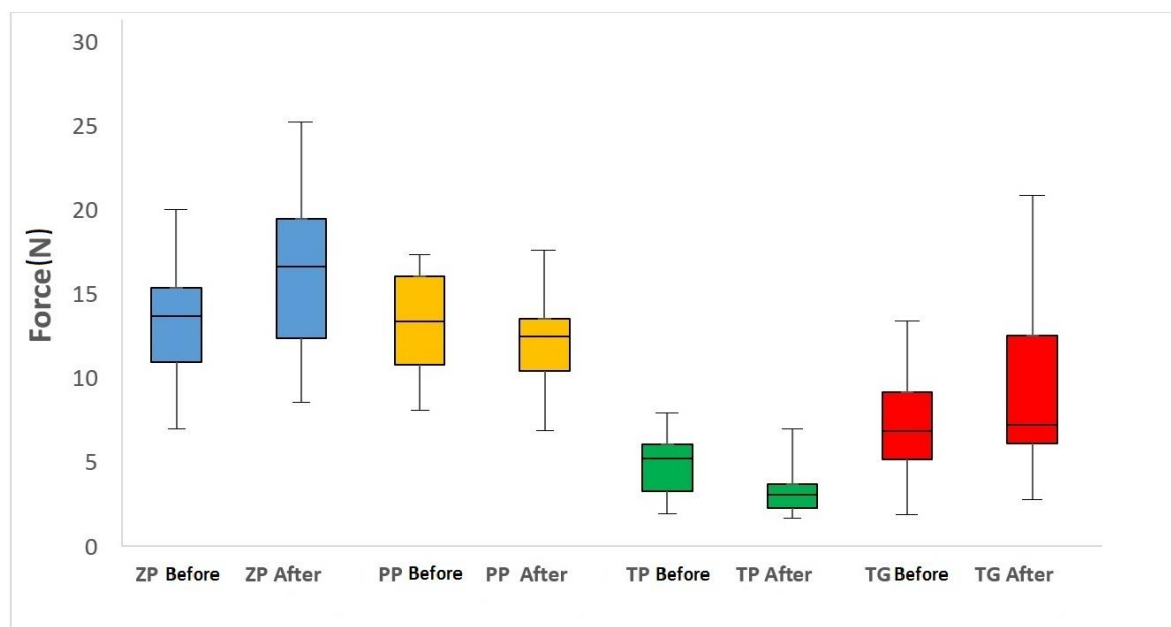


Figure 20. Box-plot curve representing the retention force in N before and after performing the thermo-mechanical dynamic loading test. Group codes see Table 1, page 15.

5. Discussion

5.1. Discussion of the methods

In the current study, the clinical situation of a double crown-retained overdenture on four implants was simulated. Most laboratory studies have been investigating the retention of different double crown systems using only one retainer with different parameters being measured (3, 9, 16, 52, 60). However, for a double crown-retained overdenture four implants are usually recommended as a minimal number of implants to insure durable retention and to prevent implant overloading (13, 59).

The secondary crowns were positioned parallel in the testing machine so that the pull-off direction of the testing machine was perpendicular. The used preload of 98 N and the pull-off speed of 7 mm/sec were a compromise of the values extracted from the known clinical tests, together with the possible technical settings. In patients wearing implant-supported overdentures, the average reported chewing force was 50 N, while the maximum bite force was 144 N (30). Furthermore, two sets of the load; 50 and 100 N were used to investigate the effect of the taper and space settings of tapered double crowns on the retention and settling (50). Therefore, based on the cumulative reported data, we selected the preload exerted on the outer framework in the present study. Similar studies proved a relation between the speed of the prosthesis removal and retention due to the hydraulic system of the electroplated conical double-crown (3, 4, 28). Based on their results as well as based on a pilot study we performed initially, a speed of 7 mm/sec was chosen. The 10,000 insertion/separation cycles corresponded to approximately 10 years of removing and inserting the denture three times daily (4, 6, 67). Moreover, it has been shown that 10,000 cycles of insertion and separation are optimal for significant changes of retention to occur (47), and that an almost constant level of retention force was obtained after 5,000 cycles (4).

The specimens were immersed in water at room temperature to simulate the moist intraoral conditions. Moreover, the wet conditions ensured the removal of wear products outside the friction area (3, 20, 53, 55). Furthermore, using electroformed copings, a medium between the primary and secondary crown was required to aid

building up hydraulic adhesion in-between (9, 72). In the current study, we used water as a standard medium with all study groups. However, the viscosity and the amount of the medium can influence the retentive force. In a clinical situation, increasing the viscosity of the saliva may increase the adhesion. Therefore, a clinical evaluation of the amount and viscosity of the patient's saliva would be appropriate before choosing a suitable type of the material used (9).

PEEK was thoroughly investigated to improve its surface properties as it has low surface energy and is resistant to surface modification by different chemical treatments, therefore it has inadequate bond strength with composite resin materials. To overcome such problem, a combined pretreatment of the surface by chemical method as well as mechanical treatment using air abrasion are recommended to improve the initial bond strength significantly (58, 64). In a study investigating the influence of surface conditioning on bonding to PEEK, surface roughness using air abrasion alone was insufficient to achieve durable bonding to PEEK; however, applying a multifunctional methacrylates containing resin varnish on air-abraded PEEK surfaces yielded durable bonding to PEEK (38). Visio.link is a polymethyl methacrylates based adhesive system. In the current study, PEEK abutments were steam-cleaned and air-abraded using 110 μm alumina particles then conditioned with Visio.link just before applying the composite adhesive cement to be bonded to the titanium bases. The electroformed secondary crowns were bonded to a supporting metal framework, which is required to obtain sufficient stability of the secondary crowns (20).

In the present investigation, the abutments were designed and finished at 1° taper. In a recent study, a taper of 0°, 1° and 2° were examined and the highest retention was achieved with 1° taper (46). Furthermore, achieving good retention of double crowns is a very sensitive and precise procedure that depends on various factors such as the milling speed, the degree of wear of the cutters, the polishing procedures, the casting technique, and the method of setting the retention force (5, 28). In the current study, the production and the finishing process were standardized as much as possible. Moreover, the PEEK frameworks were tested in the universal testing machine to ensure similarity of the initial

retention value among the eight specimens of each test group, as the manual manufacturing injection technique cannot be perfectly standardized.

A direct relationship between the retention of the prosthesis and the patient satisfaction was reported (10). In order to evaluate the retention of the implant attachments, the maximum dislodging force (peak load) should be accurately measured. It represents the resistance of the overdenture to be removed from the abutments. The peak load plays an important role in selecting the proper type of prosthesis in different clinical situations. Likewise, the degree of wear, during the lifetime of the attachments, represents a basic function in maintaining retention over time (54). Hence, the current study aimed to determine the prosthesis retention, which is the maximum force developed before the complete separation of double crown components, and to evaluate the change in the retention over 10,000 insertion/separation cycles.

Wagner et al. and Merk et al. identified some limitations in their studies concerning simulating the oral environment conditions, which should be considered as cyclic fatigue loading, which could significantly weaken the retention load of the telescopic crowns. In addition, they both did not simulate any thermodynamic loading in their studies (46, 71). In the present study, the thermo-mechanical dynamic loading test aimed to analyze the changes of retention force of telescopic overdenture after dynamic loading conditions simulating the rotational movement of implant supported overdenture with thermo-cycling in temperature ranged between 5 °C and 55 °C (34). The specimens were subjected to a dynamic loading for 1,200,000 chewing cycles, which corresponds approximately to 5 years of clinical service (37).

A vertical load of 60 N was applied on the loading point at a speed of 30 mm/sec as used by other studies (3, 34), that was applied during the chewing simulation test which allowed the bottom of the screw to touch the metal top fixed to the PVC base.

Before and after the thermo-mechanical dynamic loading test, the retentive force of each specimen was measured 10 times using the universal testing machine with a 50 N repeated load and a speed of 8 mm/sec. This approach is in agreement with other

comparable studies which repeated a similar measurement technique for 10 times to prevent any coincidence of results (9, 27, 72).

In the present study, two separate tests were performed with the same specimens; insertion/separation cycles and subsequently the thermo-mechanical dynamic loading test. Two different approaches in measuring the retentive force have been used, which might have resulted in reporting different values of retention.

During the insertion/separation cycles, the retentive force was directly measured in the chewing simulator. For the thermo-mechanical dynamic loading test, the universal testing machine was used to measure the retentive force before and after applying the chewing cycles. Due to technical limitations regarding the design of the specimens, in the universal testing machine not the same fitting load as in the chewing simulator could be applied, which resulted in reduced values of the measured retentive force. Weigl et al. also found that applying less fitting load resulted in lower values of retentive force of the same double crown specimens (72).

Despite the obvious difference in the reported retention values of the two tests, each test was performed under standardized conditions and parameters. Therefore, the results of each test are valid and could be used for analysis.

5.2. Discussion of the results

After 10,000 insertion/separation cycles, the electroformed control group (TG) showed lower retention than the other groups. This difference could be attributed to the production process, as the direct construction of gold crowns by the electroforming process established an optimal fitting (55). Likewise, the electroforming process attains a smooth internal coping surface and does not require any manual adjustment (4, 72). For the manufacturing of the PEEK frameworks, the material was invested and injected. Afterwards, a manual adjustment of retention force was necessary to reduce strain between the abutments. Still, the final prosthesis retention was higher than that of the TG group. In a study by Engels et al., the electroformed crowns showed lower retention compared with cast ones (20). Furthermore, secondary cast crowns (telescopic and conical) mainly adhere through friction and wedging, whereas galvanic crowns basically adhere by hydraulic adhesion (66). It can be presumed that the variation in the values is

not only material dependent, but also strongly influenced by the manufacturing techniques (71). An increase in the retention force was noticed to be dependent on the increase of the preload force of the double crowns with secondary cast crowns. However, this effect was not observed for the double crowns with electroformed secondary crowns at preloads between 10 and 300 N (72). All these factors may explain the difference in retention force between the control group TG and the other test groups in the present study.

The degree of wear may either increase or decrease as a result of the relative movement between the surfaces of the copings depending on whether the elevated areas of the material are abraded and leveled, or other areas are broken off. The subsequent change of the retentive forces may decrease, remain unchanged, or even increase, as the surfaces at the wear tracks may interlock leading to an increase in the retentive force. Additional wear may occur and the firmly wedged contact would be replaced by a gap and the retentive force is reduced. Despite the fact that the manually produced copings were constructed by the same operator using identical methods, the behavior of the retentive force may still be unpredictable depending on the effect of wear (72). In a previous study, different combinations of gold, titanium and CoCr for both inner and outer crowns were tested, and the study showed that the mean retention increased over 10,000 insertion and separation cycles (7). This increase was likely due to the mechanical adaptation at the level of the interface between the inner and the outer crowns. A decrease in the retention force due to metal abrasion over long-term use was not observed in any of the specimens. Therefore, the difference in mechanical adaptation of different materials, finishing of the primary crowns, construction of the secondary crowns, different physical properties and wear of the different materials could explain the observed slight increase in retention in groups PP and TP, as well as the slight decrease observed in group TC, and the observed higher level of retention of group ZP in comparison to other groups.

PEEK double crowns showed promising results compared to zirconia, titanium and electroformed gold materials. PEEK could be efficiently used as primary, secondary, or for both crowns. Nonetheless, these results should be considered as basic initial testing

of the PEEK material in combination with approved materials, such as CoCr, ZrO₂, and electroformed crowns (65).

After the thermo-mechanical dynamic loading test, there was no statistically significant change in the retentive force in groups PP and TG. On the contrary, there was a statistically significant increase in the retentive force within group ZP and a statistically significant decrease in the retentive force within group TP. However, this change in the retentive force seems minimal and not clinically relevant.

This study, and other published research aim at identifying the amount of retention necessary to produce a functional reliable telescopic overdenture (7, 20, 71, 72). Based on the promising results from the present study, further laboratory and clinical examinations as well as monitoring patient satisfaction are justified.

6. Conclusion

Within the limitations of this laboratory study, the use of metallic and non-metallic combinations in the construction of double crown-retained mandibular overdentures resulted in acceptable and durable levels of prosthesis retention, which might be suitable for clinical application. Clinical studies are required to support the use of PEEK for double crowns.

7. Summary

The aim of the current study was to evaluate the change in retention of novel metallic and non-metallic combinations for double crown-retained overdentures on implants.

Polyvinylchloride-cylindrical bases were used to insert four implants arranged in a lower arch, with 10 mm inter-implant spacing anteriorly and 35 mm posteriorly. Five groups (n=8 each) of different materials combinations were tested: zirconia abutments/PEEK framework (ZP), PEEK abutments/PEEK framework (PP), titanium abutments/PEEK framework (TP), titanium abutments/CoCr framework (TC), and titanium abutments/gold copings/cobalt-chromium framework as control group (TG). The abutment retention height was 4 mm with 1° convergence angle.

The retention was measured in a wet condition using a chewing simulator initially, and then after 100, 200, 500, 1,000, 2,000, 3,000, 5,000, 8,000, and 10,000 insertion/separation cycles, which simulates removing and inserting of an overdenture three times daily for 10 years of function. Subsequently, the specimens were subjected to thermo-mechanical dynamic load distally located in a chewing simulator for 1,200,000 loading cycles with 60 N corresponding to 5-years clinical fatigue. A universal testing device was used to measure the retentive force before and after the chewing simulation.

The initial median retention of all groups ranged from 10.0 to 33.3 N. After 10,000 insertion/separation cycles, the median retention ranged from 10.3 to 35.0 N. The change in the retention after 10,000 cycles was not statistically significant within groups ZP and TG. For groups PP and TP, there was slight increase in retention with partial significance. The retention of group TC showed fluctuation with partially significant decrease of retention.

Regarding the thermo-mechanical dynamic loading test, the initial mean retention of all groups ranged from 4.9 to 13.2 N. After 1,200,000 chewing cycles, the mean retention ranged from 3.3 to 16.4 N. There was no statistically significant change in

retention in groups PP and TG. However, in groups ZP and TP the retention changed significantly.

Based on the results of this study, the use of novel metallic and non-metallic combinations in the construction of double crown-retained mandibular overdentures on implants resulted in acceptable and durable levels of retention. Therefore, their clinical evaluation seems justified.

8. Zusammenfassung

Zielsetzung der vorgelegten Arbeit war die Untersuchung der Haftkräfte unterschiedlicher neuartiger metallischer und nichtmetallischer Materialkombinationen bei der Konstruktion von Doppelkronen.

Mit Polyvinylchlorid-Zylinderbasen wurden vier in einem Bogen angeordnete Implantate mit einem Abstand zwischen den Implantaten von 10 mm anterior und 35 mm posterior eingesetzt. Fünf Gruppen (jeweils n=8) verschiedener Materialkombinationen wurden getestet: Zirkoniumdioxid-Abutments/PEEK-Gerüst (ZP), PEEK-Abutments/PEEK-Gerüst (PP), Titan-Abutments/PEEK-Gerüst (TP), Titan-Abutments/CoCr-Gerüst (TC) und Titan-Abutments/Goldkappen/Kobalt-Chrom-Gerüst als Kontrollgruppe (TG). Die Retentionshöhe der Abutments betrug 4 mm mit einem Konvergenzwinkel von 1°.

Die Haltekräfte wurden zunächst unter Verwendung einer feuchten Bedingung mit einem Kausimulator und dann nach 100, 200, 500, 1.000, 2.000, 3.000, 5.000, 8.000 und 10.000 Füge-/Trennungszyklen gemessen, wodurch das Entfernen und Einsetzen einer Deckprothese dreimal täglich über 10 Jahre simuliert wurde. Anschließend wurden die Proben in einem Kausimulator 1,2 Million Zyklen mit dynamischer Belastung von 60 N und thermischen Zyklen ausgesetzt, was einer klinischen Ermüdung von 5 Jahren entspricht. Eine Universalprüfmaschine wurde zur Messung der Haltekraft vor und nach der Kausimulation verwendet.

Die initialen Mediane der Haftkräfte aller Gruppen lag zwischen 10,0 und 33,3 N. Nach 10.000 Füge-/Trennungszyklen lagen die Mediane zwischen 10,3 und 35,0 N. Die Veränderung der Haftkräfte nach 10.000 Zyklen war innerhalb der Gruppen ZP und TG statistisch nicht signifikant. Bei den Gruppen PP und TP gab es teilweise einen signifikanten Anstieg der Haftkräfte. Die Ergebnisse der Gruppe TC zeigte eine Fluktuation mit teilweise signifikanter Abnahme der Haftkräfte.

Hinsichtlich des thermomechanisch-dynamischen Belastungstests lagen die initialen Mittelwerte der Haftkräfte aller Gruppen zwischen 4,9 und 13,2 N. Nach

1.200.000 Kauzyklen lagen die Mittelwerte der Haftkräfte zwischen 3,3 und 16,4 N. Es gab keine signifikanten Änderungen der Haftkräfte in den Gruppen PP und TG. Jedoch veränderten sich die Haftkräfte der Gruppen ZP und TP signifikant.

Aus den Ergebnissen der Studie lässt sich schlussfolgern, dass die Verwendung neuartiger metallischer und nichtmetallischer Materialkombinationen bei der Konstruktion von Doppelkronen zu akzeptablen und dauerhaften Haftkräften führt. Daher erscheint ihre klinische Erprobung gerechtfertigt.

9. References

- [1] Akagawa Y, Seo T, Ohkawa S, Tsuru H. A new telescopic crown system using a soldered horizontal pin for removable partial dentures. *J Prosthet Dent.* 1993;69:228-31.
- [2] Alsabeeha NH, Payne AG, Swain MV. Attachment systems for mandibular two-implant overdentures: a review of in vitro investigations on retention and wear features. *Int J Prosthodont.* 2009;22:429-40.
- [3] Bayer S, Zuziak W, Kraus D, Keilig L, Stark H, Enkling N. Conical crowns with electroplated gold copings: retention force changes caused by wear and combined off-axial load. *Clin Oral Implants Res.* 2011;22:323-9.
- [4] Bayer S, Kraus D, Keilig L, Golz L, Stark H, Enkling N. Wear of double crown systems: electroplated vs. casted female part. *J Appl Oral Sci.* 2012;20:384-91.
- [5] Bayer S, Stark H, Mues S, Keilig L, Schrader A, Enkling N. Retention force measurement of telescopic crowns. *Clin Oral Investig.* 2010;14:607-11.
- [6] Besimo C, Guarneri A. In vitro retention force changes of prefabricated attachments for overdentures. *J Oral Rehabil.* 2003;30:671-8.
- [7] Besimo C, Graber G, Fluhler M. Retention force changes in implant-supported titanium telescope crowns over long-term use in vitro. *J Oral Rehabil.* 1996;23:372-8.
- [8] Besimo C, Graber G. A new concept of overdentures with telescope crowns on osseointegrated implants. *Int J Periodontics Restorative Dent.* 1994;14:486-95.
- [9] Beuer F, Edelhoff D, Gernet W, Naumann M. Parameters affecting retentive force of electroformed double-crown systems. *Clin Oral Investig.* 2010;14:129-35.
- [10] Burns DR, Unger JW, Elswick RK, Jr., Giglio JA. Prospective clinical evaluation of mandibular implant overdentures: Part II--Patient satisfaction and preference. *J Prosthet Dent.* 1995;73:364-9.
- [11] Campbell SD, Cooper L, Craddock H, Hyde TP, Nattress B, Pavitt SH, Seymour DW. Removable partial dentures: The clinical need for innovation. *J Prosthet Dent.* 2017;118:273-80.
- [12] Celik Guven M, Tuna M, Bozdog E, Ozturk GN, Bayraktar G. Comparison of retention forces with various fabrication methods and materials in double crowns. *J Adv Prosthodont.* 2017;9:308-14.
- [13] Cepa S, Koller B, Spies BC, Stampf S, Kohal RJ. Implant-retained prostheses: ball vs. conus attachments - A randomized controlled clinical trial. *Clin Oral Implants Res.* 2017;28:177-85.
- [14] Cune MS, Verhoeven JW, Meijer GJ. A prospective evaluation of Frialoc implants with ball-abutments in the edentulous mandible: 1-year results. *Clin Oral Implants Res.* 2004;15:167-73.
- [15] Dabrowa T, Dobrowolska A, Wieleba W. The role of friction in the mechanism of retaining the partial removable dentures with double crown system. *Acta Bioeng Biomech.* 2013;15:43-8.
- [16] Di Felice R, Rappelli G, Camaioni E, Cattani M, Meyer JM, Belser UC. Cementable implant crowns composed of cast superstructure frameworks luted to electroformed primary copings: an in vitro retention study. *Clin Oral Implants Res.* 2007;18:108-13.
- [17] Egusa H, Ko N, Shimazu T, Yatani H. Suspected association of an allergic reaction with titanium dental implants: a clinical report. *J Prosthet Dent.* 2008;100:344-7.
- [18] Eitner S, Schlegel A, Emeka N, Holst S, Will J, Hamel J. Comparing bar and double-crown attachments in implant-retained prosthetic reconstruction: a follow-up investigation. *Clin Oral Implants Res.* 2008;19:530-7.
- [19] Elsyad MA, Khairallah AS, Shawky AF. Changes in the edentulous maxilla with ball and telescopic attachments of implant-retained mandibular overdentures: a 4-year retrospective study. *Quintessence Int.* 2013;44:487-95.
- [20] Engels J, Schubert O, Guth JF, Hoffmann M, Jauernig C, Erdelt K, Stimmelmayer M, Beuer F. Wear behavior of different double-crown systems. *Clin Oral Investig.* 2013;17:503-10.
- [21] Evtimovska E, Masri R, Driscoll CF, Romberg E. The change in retentive values of locator attachments and hader clips over time. *J Prosthodont.* 2009;18:479-83.
- [22] Feine JS, Carlsson GE, Awad MA, Chehade A, Duncan WJ, Gizani S, Head T, Lund JP, MacEntee M, Mericske-Stern R, Mojon P, Morais J, Naert I, Payne AG, Penrod J, Stoker GT, Tawse-Smith A, Taylor

- TD, Thomason JM, Thomson WM, Wismeijer D. The McGill consensus statement on overdentures. Mandibular two-implant overdentures as first choice standard of care for edentulous patients. Montreal, Quebec, May 24-25, 2002. *Int J Oral Maxillofac Implants*. 2002;17:601-2.
- [23] Frisch E, Ziebolz D, Rinke S. Long-term results of implant-supported over-dentures retained by double crowns: a practice-based retrospective study after minimally 10 years follow-up. *Clin Oral Implants Res*. 2013;24:1281-7.
- [24] Frisch E, Ziebolz D, Ratka-Krüger P, Rinke S. Double crown-retained maxillary overdentures: 5-year follow-up. *Clin Implant Dent Relat Res*. 2015;17:22-31.
- [25] Gotfredsen K, Holm B. Implant-supported mandibular overdentures retained with ball or bar attachments: a randomized prospective 5-year study. *Int J Prosthodont*. 2000;13:125-30.
- [26] Greven B, Luepke M, von Dorsche SH. Telescoping implant prostheses with intraoral luted galvano mesostructures to improve passive fit. *J Prosthet Dent*. 2007;98:239-44.
- [27] Güngör MA, Artunc C, Sonugelen M. Parameters affecting retentive force of conus crowns. *J Oral Rehabil*. 2004;31:271-7.
- [28] Gurbulak AG, Kilic K, Eroglu Z, Gercekcioglu E, Kesim B. Evaluation of the retention force of double conical crowns used in combination with a galvanofarming and casting fabrication technique. *J Prosthodont*. 2013;22:63-8.
- [29] Hahnel S, Wieser A, Lang R, Rosentritt M. Biofilm formation on the surface of modern implant abutment materials. *Clin Oral Implants Res*. 2015;26:1297-301.
- [30] Haraldson T, Carlsson GE. Bite force and oral function in patients with osseointegrated oral implants. *Scand J Dent Res*. 1977;85:200-8.
- [31] Heckmann SM, Schrott A, Graef F, Wichmann MG, Weber HP. Mandibular two-implant telescopic overdentures. *Clin Oral Implants Res*. 2004;15:560-9.
- [32] Heckmann SM, Winter W, Meyer M, Weber HP, Wichmann MG. Overdenture attachment selection and the loading of implant and denture-bearing area. Part 2: A methodical study using five types of attachment. *Clin Oral Implants Res*. 2001;12:640-7.
- [33] Hoffmann O, Beaumont C, Tatakis DN, Zafiropoulos GG. Telescopic crowns as attachments for implant supported restorations: a case series. *J Oral Implantol*. 2006;32:291-9.
- [34] Jo DW, Dong JK. Effects of posterior ridge resorption and attachment wear on periimplant strain in mandibular two-implant-supported overdentures. *J Prosthet Dent*. 2015;114:839-47.
- [35] Kanbara T, Yajima Y, Yoshinari M. Wear behavior of tetragonal zirconia polycrystal versus titanium and titanium alloy. *Biomed Mater*. 2011;6:021001.
- [36] Kern JS, Kern T, Wolfart S, Heussen N. A systematic review and meta-analysis of removable and fixed implant-supported prostheses in edentulous jaws: post-loading implant loss. *Clin Oral Implants Res*. 2016;27:174-95.
- [37] Kern M, Strub JR, Lu XY. Wear of composite resin veneering materials in a dual-axis chewing simulator. *J Oral Rehabil*. 1999;26:372-8.
- [38] Kern M, Lehmann F. Influence of surface conditioning on bonding to polyetheretherketon (PEEK). *Dent Mater*. 2012;28:1280-3.
- [39] Krennmair G, Suto D, Seemann R, Piehslinger E. Removable four implant-supported mandibular overdentures rigidly retained with telescopic crowns or milled bars: a 3-year prospective study. *Clin Oral Implants Res*. 2012;23:481-8.
- [40] Kurtz SM, Devine JN. PEEK biomaterials in trauma, orthopedic, and spinal implants. *Biomaterials*. 2007;28:4845-69.
- [41] Kutkut A, Bertoli E, Frazer R, Pinto-Sinai G, Fuentealba Hidalgo R, Studts J. A systematic review of studies comparing conventional complete denture and implant retained overdenture. *J Prosthodont Res*. 2018;62:1-9.
- [42] Langer A. Telescope retainers and their clinical application. *J Prosthet Dent*. 1980;44:516-22.
- [43] Lucas LC, Lemons JE. Biodegradation of restorative metallic systems. *Adv Dent Res*. 1992;6:32-7.
- [44] Mericske-Stern RD, Taylor TD, Belser U. Management of the edentulous patient. *Clin Oral Implants Res*. 2000;11 Suppl 1:108-25.

- [45] Merk S, Wagner C, Stock V, Eichberger M, Schmidlin PR, Roos M, Stawarczyk B. Suitability of secondary PEEK telescopic crowns on zirconia primary crowns: The influence of fabrication method and taper. *Materials (Basel)*. 2016;9:908.
- [46] Merk S, Wagner C, Stock V, Schmidlin PR, Roos M, Eichberger M, Stawarczyk B. Retention load values of telescopic crowns made of Y-TZP and CoCr with Y-TZP secondary crowns: impact of different taper angles. *Materials (Basel)*. 2016;9:354.
- [47] Minagi S, Natsuaki N, Nishigawa G, Sato T. New telescopic crown design for removable partial dentures. *J Prosthet Dent*. 1999;81:684-8.
- [48] Naert I, Gizani S, Vuylsteke M, van Steenberghe D. A 5-year randomized clinical trial on the influence of splinted and unsplinted oral implants in the mandibular overdenture therapy. Part I: Peri-implant outcome. *Clin Oral Implants Res*. 1998;9:170-7.
- [49] Naert I, Gizani S, Vuylsteke M, Van Steenberghe D. A 5-year prospective randomized clinical trial on the influence of splinted and unsplinted oral implants retaining a mandibular overdenture: prosthetic aspects and patient satisfaction. *J Oral Rehabil*. 1999;26:195-202.
- [50] Nakagawa S, Torii K, Tanaka M. Effects of taper and space settings of telescopic Ce-TZP/A crowns on retentive force and settling. *Dent Mater J*. 2017;36:230-5.
- [51] Ohida M, Yoda K, Nomura N, Hanawa T, Igarashi Y. Evaluation of the static frictional coefficients of Co-Cr and gold alloys for cone crown telescope denture retainer applications. *Dent Mater J*. 2010;29:706-12.
- [52] Ohkawa S, Okane H, Nagasawa T, Tsuru H. Changes in retention of various telescope crown assemblies over long-term use. *J Prosthet Dent*. 1990;64:153-8.
- [53] Passia N, Ghazal M, Kern M. Long-term retention behaviour of resin matrix attachment systems for overdentures. *J Mech Behav Biomed Mater*. 2016;57:88-94.
- [54] Petropoulos VC, Smith W. Maximum dislodging forces of implant overdenture stud attachments. *Int J Oral Maxillofac Implants*. 2002;17:526-35.
- [55] Pietruski JK, Sajewicz E, Sudnik J, Pietruska MD. Retention force assessment in conical crowns in different material combinations. *Acta Bioeng Biomech*. 2013;15:35-42.
- [56] Rammelsberg P, Bernhart G, Lorenzo Bermejo J, Schmitter M, Schwarz S. Prognosis of implants and abutment teeth under combined tooth-implant-supported and solely implant-supported double-crown-retained removable dental prostheses. *Clin Oral Implants Res*. 2014;25:813-8.
- [57] Rashid F, Awad MA, Thomason JM, Piovano A, Spielberg GP, Scilingo E, Mojon P, Muller F, Spielberg M, Heydecke G, Stoker G, Wismeijer D, Allen F, Feine JS. The effectiveness of 2-implant overdentures - a pragmatic international multicentre study. *J Oral Rehabil*. 2011;38:176-84.
- [58] Rocha RF, Anami LC, Campos TM, Melo RM, Souza RO, Bottino MA. Bonding of the polymer polyetheretherketone (PEEK) to human dentin: effect of surface treatments. *Braz Dent J*. 2016;27:693-9.
- [59] Romanos GE, May S, May D. Treatment concept of the edentulous mandible with prefabricated telescopic abutments and immediate functional loading. *Int J Oral Maxillofac Implants*. 2011;26:593-7.
- [60] Sakai Y, Takahashi H, Iwasaki N, Igarashi Y. Effects of surface roughness and tapered angle of cone crown telescopic system on retentive force. *Dent Mater J*. 2011;30:635-41.
- [61] Schwindling FS, Lehmann F, Terebesi S, Corcodel N, Zenthofer A, Rammelsberg P, Stober T. Electroplated telescopic retainers with zirconia primary crowns: 3-year results from a randomized clinical trial. *Clin Oral Investig*. 2017;21:2653-60.
- [62] Schwitalla AD, Spintig T, Kallage I, Muller WD. Flexural behavior of PEEK materials for dental application. *Dent Mater*. 2015;31:1377-84.
- [63] Shimakura M, Nagata T, Takeuchi M, Nemoto T. Retentive force of pure titanium konus telescope crowns fabricated using CAD/CAM system. *Dent Mater J*. 2008;27:211-5.
- [64] Stawarczyk B, Beuer F, Wimmer T, Jahn D, Sener B, Roos M, Schmidlin PR. Polyetheretherketone-a suitable material for fixed dental prostheses? *J Biomed Mater Res B Appl Biomater*. 2013;101:1209-16.

- [65] Stock V, Wagner C, Merk S, Roos M, Schmidlin PR, Eichberger M, Stawarczyk B. Retention force of differently fabricated telescopic PEEK crowns with different tapers. *Dent Mater J*. 2016;35:594-600.
- [66] Stock V, Schmidlin PR, Merk S, Wagner C, Roos M, Eichberger M, Stawarczyk B. PEEK primary crowns with cobalt-chromium, zirconia and galvanic secondary crowns with different tapers-A comparison of retention forces. *Materials (Basel)*. 2016;9:187.
- [67] Tannous F, Steiner M, Shahin R, Kern M. Retentive forces and fatigue resistance of thermoplastic resin clasps. *Dent Mater*. 2012;28:273-8.
- [68] Turk PE, Geckili O, Turk Y, Gunay V, Bilgin T. In vitro comparison of the retentive properties of ball and locator attachments for implant overdentures. *Int J Oral Maxillofac Implants*. 2014;29:1106-13.
- [69] van Kampen F, Cune M, van der Bilt A, Bosman F. Retention and postinsertion maintenance of bar-clip, ball and magnet attachments in mandibular implant overdenture treatment: an in vivo comparison after 3 months of function. *Clin Oral Implants Res*. 2003;14:720-6.
- [70] Verma R, Joda T, Brägger U, Wittneben JG. A systematic review of the clinical performance of tooth-retained and implant-retained double crown prostheses with a follow-up of ≥ 3 years. *J Prosthodont*. 2013;22:2-12.
- [71] Wagner C, Stock V, Merk S, Schmidlin PR, Roos M, Eichberger M, Stawarczyk B. Retention load of telescopic crowns with different taper angles between cobalt-chromium and polyetheretherketone made with three different manufacturing processes examined by pull-off test. *J Prosthodont*. 2018;27:162-8.
- [72] Weigl P, Hahn L, Lauer HC. Advanced biomaterials used for a new telescopic retainer for removable dentures. *J Biomed Mater Res*. 2000;53:320-36.
- [73] Wenz HJ, Hertrampf K, Lehmann KM. Clinical longevity of removable partial dentures retained by telescopic crowns: outcome of the double crown with clearance fit. *Int J Prosthodont*. 2001;14:207-13.
- [74] Wismeijer D, Vermeeren JI, van Waas MA. Patient satisfaction with overdentures supported by one-stage TPS implants. *Int J Oral Maxillofac Implants*. 1992;7:51-5.
- [75] Witkowski S, Komine F, Gerds T. Marginal accuracy of titanium copings fabricated by casting and CAD/CAM techniques. *J Prosthet Dent*. 2006;96:47-52.
- [76] Wöstmann B, Balkenhol M, Weber A, Ferger P, Rehmann P. Long-term analysis of telescopic crown retained removable partial dentures: survival and need for maintenance. *J Dent*. 2007;35:939-45.
- [77] Zafiropoulos GG, Rebbe J, Thielen U, Deli G, Beaumont C, Hoffmann O. Zirconia removable telescopic dentures retained on teeth or implants for maxilla rehabilitation. Three-year observation of three cases. *J Oral Implantol*. 2010;36:455-65.
- [78] Zafiropoulos GG, Hoffmann O. Five-year study of implant placement in regenerated bone and rehabilitation with telescopic crown retained dentures: a case report. *J Oral Implantol*. 2009;35:303-9.

10. Acknowledgement

I would like to express my deepest thanks and appreciation to my supervisor Prof. Dr. Matthias Kern, chairman of the Department of Prosthodontics, Propaedeutics and Dental Materials, Christian-Albrechts University at Kiel for his support and driving force throughout this work.

I am deeply grateful to Dr. Ashraf Amer, professor of prosthodontics, faculty of oral and dental medicine, Cairo University for his scientific input, and valuable advice during my work.

I am indebted to Dr. M. Sad Chaar, senior lecturer in the Department of Prosthodontics, Propaedeutics and Dental Materials, Christian-Albrechts University at Kiel for his continues support and supervision during the progress of the work and his help in overcoming technical obstacles.

I am most grateful to Dr. Amr Elkhadem assistant professor of prosthodontics, faculty of oral and dental medicine, Cairo university for his valuable advices, his unlimited generosity and support.

I am also deeply grateful for Dr. Sebastian Wille for his help during the testing on chewing simulator and also for his valuable advices in statistical analysis.

I would like to thank all the team of the dental laboratory especially Mr. Reinhard Busch for his technical advice.

Finally, I would like to gratefully acknowledge the Bredent company for donating the study material as well as the Gramm Technik company, who provided the gold copings. Also, Schütz Dental company for providing the CoCr frameworks.

11. Dedication

This work is dedicated to my late father, my beloved mother, my brothers, sister, all my family and friends for their unconditional love and support.

I would like also to dedicate my work to my lovely daughter Aya. Finally, and most importantly, to my husband Tamer, his support, encouragement, quiet patience and unwavering love were undeniably the bedrock, on which I always rely.

12. Appendixes

Retention values of Group ZP												
Cycle	0	100	200	300	400	500	1000	2000	3000	5000	8000	10000
1.Specimen	42.8	41.2	40.1	39.7	39.9	39.3	36.6	35.1	35.0	36.7	35.8	35.7
2.Specimen	36.1	35.6	34.4	34.0	34.0	34.0	32.4	30.3	29.7	28.7	29.9	30.2
3.Specimen	24.0	26.7	26.7	26.6	26.8	27.1	26.7	25.9	25.2	25.1	25.1	25.4
4 Specimen	30.4	28.4	29.7	29.6	29.9	30.2	32.1	36.7	39.1	44.5	45.6	45.2
5.Specimen	27.9	35.6	35.3	33.3	34.4	37.2	39.5	42.1	41.3	43.3	42.0	40.4
6.Specimen	39.6	33.9	34.3	34.8	35.0	35.2	36.7	35.2	35.5	34.5	34.7	34.2
7.Specimen	27.3	29.3	30.7	31.4	32.1	33.0	37.7	45.2	48.1	43.4	36.0	37.4
8.Specimen	36.6	43.9	38.6	36.6	36.3	35.6	35.1	34.3	32.6	31.1	33.4	32.7
Mean	33.1	34.3	33.7	33.2	33.5	34.0	34.6	35.6	35.8	35.9	35.3	35.2
SD	6.7	6.1	4.5	4.1	4.0	3.9	4.1	6.1	7.1	7.4	6.4	6.1
Median	33.3	34.8	34.4	33.7	34.2	34.6	35.9	35.1	35.3	35.6	35.2	35.0

Retention values of Group PP												
Cycle	0	100	200	300	400	500	1000	2000	3000	5000	8000	10000
1.Specimen	21.0	22.3	22.7	22.9	23.1	23.2	23.6	22.6	22.1	19.4	21.5	21.0
2.Specimen	20.4	22.5	22.5	22.4	22.5	22.6	22.8	23.4	23.6	24.9	25.3	26.6
3.Specimen	20.7	27.3	28.3	28.5	28.4	28.6	28.8	28.5	28.6	28.5	29.0	28.5
4.Specimen	21.7	24.8	26.4	27.6	27.9	28.4	27.3	27.9	28.5	28.5	28.7	28.3
5.Specimen	29.9	35.6	35.5	36.1	36.1	31.3	36.4	38.0	37.9	33.0	27.0	25.8
6.Specimen	23.0	22.5	22.8	22.9	23.1	23.2	23.8	23.6	23.6	24.0	23.1	22.1
7.Specimen	20.6	24.0	24.4	24.5	25.0	25.5	25.2	26.0	26.2	25.3	30.5	32.0
8.Specimen	14.8	17.7	19.0	20.0	20.2	20.3	21.3	22.6	22.9	26.2	27.3	27.9
Mean	21.5	24.6	25.2	25.6	25.8	25.4	26.1	26.6	26.7	26.2	26.6	26.5
SD	4.1	5.2	5.0	5.1	5.0	3.7	4.8	5.2	5.2	4.0	3.1	3.6
Median	20.8	23.3	23.6	23.7	24.1	24.4	24.5	24.8	24.9	25.8	27.2	27.3

Retention values of Group TP												
Cycle	0	100	200	300	400	500	1000	2000	3000	5000	8000	10000
1.Specimen	14.8	21.2	21.1	22.2	22.8	23.1	23.9	23.1	22.8	23.0	22.0	22.3
2.Specimen	14.3	20.2	20.0	20.2	20.3	20.7	21.6	22.5	22.4	22.6	22.9	23.0
3.Specimen	11.0	19.0	19.8	20.5	21.2	21.8	22.9	23.6	23.6	24.2	24.2	24.6
4.Specimen	9.1	15.9	17.2	18.0	18.9	19.1	19.5	19.5	19.4	19.6	19.5	19.6
5.Specimen	25.4	29.8	29.6	29.3	29.0	28.5	28.8	28.2	28.1	27.8	28.2	28.5
6.Specimen	16.8	28.3	30.4	31.4	32.2	32.9	34.4	34.8	35.2	36.4	36.4	36.4
7.Specimen	17.4	30.2	31.6	32.5	32.9	33.5	33.4	33.5	33.4	32.0	30.3	30.3
8.Specimen	7.3	12.1	12.5	14.1	14.2	14.7	15.9	16.5	17.5	17.9	18.9	19.2
Mean	14.5	22.1	22.8	23.5	24.0	24.3	25.1	25.2	25.3	25.4	25.3	25.5
SD	5.7	6.7	7.0	6.7	6.7	6.7	6.6	6.5	6.4	6.3	6.0	5.9
Median	14.6	20.7	20.5	21.3	22.0	22.4	23.4	23.4	23.2	23.6	23.5	23.8

Retention values of Group TC												
Cycle	0	100	200	300	400	500	1000	2000	3000	5000	8000	10000
1.Specimen	35.4	48.3	53.9	66.4	57.3	59.1	58.6	53.3	52.0	48.9	41.2	34.7
2.Specimen	21.7	46.2	47.3	46.4	49.9	48.3	40.7	31.2	26.9	23.7	19.8	18.3
3.Specimen	37.2	34.9	33.2	31.4	32.6	32.1	33.3	29.1	29.2	21.2	16.8	16.4
4.Specimen	11.8	18.7	22.7	22.5	24.9	24.4	23.0	23.2	22.3	24.0	20.4	15.7
5.Specimen	25.4	36.8	46.8	53.3	53.1	52.4	50.5	45.2	40.1	33.9	32.8	31.5
6.Specimen	33.4	34.7	32.8	29.8	22.2	26.4	26.5	27.2	23.0	18.1	12.2	15.3
7.Specimen	15.7	17.8	22.8	22.0	22.8	23.4	20.1	20.0	18.1	15.5	8.8	7.9
8.Specimen	14.6	21.3	31.1	27.9	36.0	37.3	32.6	29.2	26.2	20.9	18.0	18.0
Mean	24.4	32.3	36.3	37.5	37.3	37.9	35.7	32.3	29.7	25.8	21.2	19.7
SD	10.0	12.0	11.7	16.1	14.3	13.8	13.5	11.2	11.1	10.8	10.7	8.9
Median	23.5	34.8	33.0	30.6	34.3	34.7	33.0	29.2	26.6	22.5	18.9	17.2

Retention values of Group TG												
Cycle	0	100	200	300	400	500	1000	2000	3000	5000	8000	10000
1.Specimen	7.4	9.6	9.7	10.9	9.9	10.2	9.9	8.8	9.3	8.1	6.9	5.9
2.Specimen	6.5	6.5	5.3	5.2	5.4	5.2	5.8	6.2	6.2	6.7	7.9	8.6
3.Specimen	20.9	17.5	16.9	16.9	17.0	16.9	16.7	16.4	16.7	16.7	20.5	20.8
4.Specimen	24.6	24.4	25.8	25.0	24.8	25.4	26.9	28.1	28.2	28.8	29.2	29.3
5.Specimen	1.5	1.4	1.4	1.4	1.4	1.4	1.3	1.3	1.4	1.5	1.6	1.5
6.Specimen	12.6	11.5	10.7	12.7	11.9	11.6	10.6	10.8	12.1	12.2	12.0	13.2
7.Specimen	13.0	15.0	14.0	12.5	12.9	12.1	11.6	10.6	10.1	9.9	10.9	12.1
8.Specimen	1.6	1.4	1.4	1.6	1.5	1.5	1.3	1.1	1.1	1.4	1.3	1.3
Mean	11.0	10.9	10.7	10.8	10.6	10.5	10.5	10.4	10.6	10.7	11.3	11.6
SD	8.4	8.0	8.3	8.0	8.0	8.1	8.4	8.8	8.8	8.9	9.5	9.6
Median	10.0	10.6	10.2	11.7	10.9	10.9	10.3	9.7	9.7	9.0	9.4	10.3

Thermo-dynamic loading test - Group ZP		
Specimens	Before	After
1. Specimen	7	9.4
2. Specimen	17.5	23.4
3. Specimen	7	8.5
4. Specimen	13.6	18.1
5. Specimen	13.7	15.6
6. Specimen	12.2	13.3
7. Specimen	20	25.2
8. Specimen	14.6	17.6

Thermo-dynamic loading test - Group PP		
Specimens	Before	After
1. Specimen	16.3	12.7
2. Specimen	8.1	6.8
3. Specimen	17.3	17.6
4. Specimen	10.3	12.8
5. Specimen	10.9	10.6
6. Specimen	14.8	15.5
7. Specimen	15.9	9.7
8. Specimen	11.9	12.2

Thermo-dynamic loading test - Group TP		
Specimens	Before	After
1. Specimen	4.8	3.5
2. Specimen	2.8	2.6
3. Specimen	1.9	1.6
4. Specimen	6.5	6.9
5. Specimen	5.6	3.6
6. Specimen	3.4	1.8
7. Specimen	7.9	2.4
8. Specimen	5.9	3.9

Thermo-dynamic loading test - Group TG		
Specimens	Before	After
1. Specimen	1.9	2.7
2. Specimen	6.3	6.7
3. Specimen	13.4	16.1
4. Specimen	9.2	11.3
5. Specimen	5.6	7.7
6. Specimen	9.1	20.8
7. Specimen	7.3	5.5
8. Specimen	3.8	6.3