Mind the gap – internal fit of fixed dental prostheses

Doctoral thesis by

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Bjørn Einar Dahl

Oslo, 1 December 2019

2. List of publications

Paper I: DAHL, B.E., RONOLD, H.J. & DAHL, J.E. Internal fit of single crowns produced by CAD-CAM and lost-wax metal casting technique assessed by the triple-scan protocol. 2017. *J Prosthet Dent*, 117, 3. 400-404.

Paper II: DAHL, B.E., DAHL, J.E. & RONOLD, H.J. Internal fit of three-unit fixed dental prostheses produced by computer-aided design/computer-aided manufacturing and the lost-wax metal casting technique assessed using the triple-scan protocol. 2018. *European Journal of Oral Sciences*, 126, 1. 66-73.

Paper III: DAHL, B.E., DAHL, J.E. & RONOLD, H.J. Digital evaluation of marginal and internal fit of single-crown fixed dental prostheses. 2018. *European Journal of Oral Sciences*, 126, 6. 512-517.

3. Abbreviations

3D	Three dimensional
3Y-TZP	3 mol% yttria stabilized tetra zirconia polycrystal
C-Co-Cr	Cast cobalt-chromium
CAD	Computer-aided design
CAM	Computer-aided manufacturing
Co-Cr	Cobalt-chromium
CNC	Computer numerical controlled
DLMS	Direct laser metal sintering
FDP	Fixed dental prosthesis
FIP	Fixed implant retained prosthesis
HIP-Zir	Hot isostatic pressed zirconium dioxide
LiSi, LDS	Lithium disilicate reinforced glass ceramic
M-Co-Cr	Milled cobalt-chromium
NC	Numerical controlled
PEEK	Polyether ether ketone
PMMA	Poly(methyl methacrylate)
RDP	Removable dental prosthesis
PSZ	Partially stabilized zirconia
SC	Single crown
SLS	Selective laser sintering
TOC	Total occlusal convergence
Zir, zirconia	Zirconium dioxide

4. Introduction

In most cultures, a bright smile with perfect teeth is associated with a healthy and successful life. The loss of tooth substance is most often the result of a carious lesion or trauma. Periodontal disease or extensive tooth wear can also result in loss of teeth. Minor loss of tooth substance is often replaced by a direct restoration, while larger loss of tooth substance, or the whole tooth, is in most instances replaced by an indirectly produced restoration.

The indirectly produced restoration can be a fixed dental prosthesis (FDP) made either from an impression in e.g. silicone and produced by the lost-wax and metal casting technique, or by digital intraoral scanning and the CAD/CAM technique, or by combinations of these methods. There are a number of opportunities for making mistakes when man is involved. To reduce the sources of error by manual labour, the CAD/CAM technique is preferred by an increasing number of dental laboratories. Besides the inevitable human errors, there are also errors due to the physical properties of the materials used, e.g. shrinkage of silicone used for impression taking, expansion of the gypsum used in the working model, or shrinkage of the wax-pattern and expansion of the metal used when casting the framework for the FDPs. Another reason for choosing the CAD/CAM technique is to reduce the number of man hours spent on producing a FDP. The long-used lost-wax and metal casting technique is a time-consuming procedure, but on the other hand it also requires less expensive equipment.

Terminology

In 1989, Holmes *et al.* described the casting misfit in this way: "*The internal gap is the perpendicular measurement from the internal surface of the casting to the axial wall of the preparation. The same measurement at the margin is termed the marginal gap. The vertical marginal misfit measured parallel to the path of insertion of the casting is termed the vertical marginal discrepancy. The horizontal marginal misfit measured perpendicular to the path of insertion is termed the horizontal marginal discrepancy. Lack of seating of a casting as measured perpendicular to the path of insertion by an arbitrary point (or points) on the external surface of the casting and tooth away from the margin is called the seating discrepancy.*" (1). In 1992, Holmes *et al.* used four different terms to describe the marginal accuracy or adaptation of fixed dental prostheses: 1) marginal gap (MG), 2) absolute marginal discrepancy (AMD), 3) vertical marginal discrepancy, and 4) horizontal marginal discrepancy (2). In 2004, Gassino *et al.* pointed out that no guidelines exist on how to perform gap measurements, nor does the term "marginal gap" have a single definition (3). The Journal of Prosthetic Dentistry prefers the term marginal and internal discrepancy to marginal and internal gap. In a private discussion with Professor Emeritus Stephen Rosenstiel, Editor of The Journal of Prosthetic Dentistry, I argued that discrepancy semantically indicated that something was wrong. Professor Rosenstiel accepted my argument and advised me to use the term marginal and internal space. Space refers to die spacer and cement space. In articles later published in The Journal of Prosthetic Dentistry it is obvious that their desired terminology is not fully implemented (4, 5).

Adaptation

A variation of terminology has been used for space between a FDP and an abutment as discussed above. For this thesis and the related papers, the terminology used is shown in Figure 1 (Papers I-III). The fit of a FDP is based on the measured marginal and internal cement space. The comparison of the fit of the various FPDs in this thesis is based on such measurements.

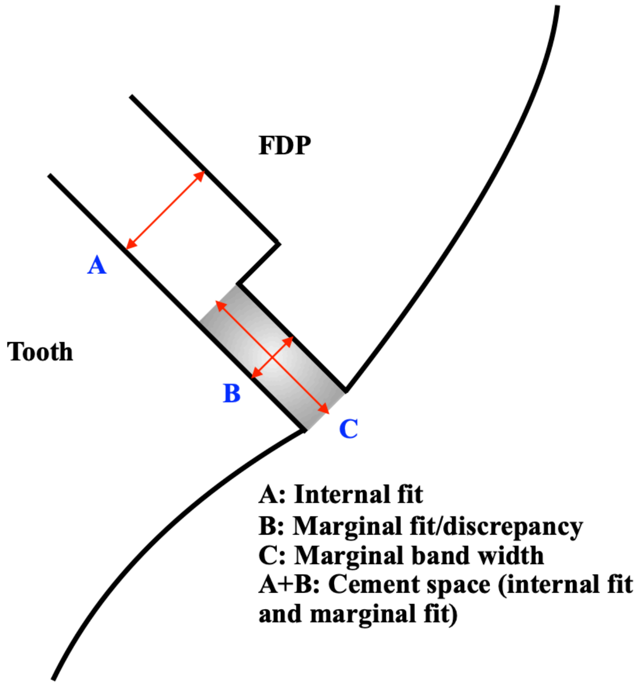

Figure 1. Schematic illustration of measurement terminology

Why is it important to measure the fit of fixed dental prostheses (FDPs)? A number of factors affect the final fit of a FDP after cementation, i.e. preparation type and taper, the amount of cement used, the viscosity of the cement, and the applied pressure during cementation (6-8). A too thin or too thick cement space (internal fit and marginal fit) may be an important cause of technical or biological complications, thus limiting the longevity of a restoration (9). Technical complications include cement fracture and loss of retention, wearing of exposed cement, shrinkage of cement during setting, and the creation of gaps next to margins. All these factors result in reduced retention and leakage. The subsequent raised bacterial activity at the marginal discrepancy may result in biological complications like caries and periodontitis (10). A marginal gap that is too wide may increase bacterial retention and cause gingival inflammation (11). The most frequent biological complications with tooth supported FDPs are loss of abutment tooth vitality and secondary caries (12). Sailer *et al.* found that the estimated survival rate after 5 years for metal-ceramic single crowns were 94.7%. This was similar to the estimated 5-year survival rate of leucite or lithium disilicate reinforced glass ceramic (96.6%), of glass infiltrated alumina (94.6%), and of densely sintered alumina and zirconia (96% and 92.1%) (13).

Wilson found the minimum axial cement space setting for water-based zinc phosphate cement to be 40 μm to achieve a marginal seating discrepancy of no more than 30 μm (14). It was suggested that particle size was the limiting factor for the cement layer thickness. Generally, the retentive ability of both water-based and resin-based cements decreases with increased film thickness (9, 15). According to International Organization for Standardization (ISO) specification ISO 9917-1 the maximum cement film thickness is 25 µm for water based cements (16). Sagen *et al.* suggested that the cement was the weakest link in bonding of zirconium dioxide and lithium disilicate reinforced glass ceramic to bovine dentine (17).

Measuring techniques for the evaluation of adaptation

In the present thesis, the evaluation of fit of FDPs was limited to the pre-cementation evaluation. Several methods have been used to estimate the thickness of the cement space. Nawafleh *et al.* (18) found that in 183 articles the direct view technique (19) had been used in 47.5% of the studies, cross-sectioning (20) had been used by 23.5%, and impression replica technique (21) had been used by 20.2%. Laser videography (22), profile projection (23), stereo microscopy (24), and micro-computed tomography (µCT) (25) are additional methods. Contrepois *et al.* concluded that use of µCT was the only method that allowed for both a satisfactory number and for an accurate analysis of measuring points (26). They also encouraged future investigators to use this method for the measurement of marginal and internal fit. Nawafleh *et al.* suggested that a combination of two measurement methods can be useful in the verification of results (18).

The triple-scan method is a more recent method based solely on digital information (27). Few studies had used this method so we found it most important to verify the method in Papers I and II. As another method described by Lee *et al.* in 2017 was even less tested, it initiated the set-up for Paper III (28). The most relevant methods are described in more detail below.

The direct view technique described by Shillingburg *et al.* measures the gap between FDP and die at the margin using a microscope (19). The internal gap is not measured. As this method does not include any dealings on the crown-die assembly such as replications of the cement space or sectioning before measuring the gap, it is cheaper and easier than other techniques. It also reduces the risk of error accumulation that may arise from multiple procedures and in the end impact the results. However, this method can only be used *in vitro* as it requires a direct view for the microscopy of the marginal gap. Nawafleh *et al.* stated that the direct view technique is the most used method in the study of marginal fit (18).

The sectioning technique described by Sorensen is a destructive way of investigating the marginal fit, or marginal *fidelity* as it is called in the article introducing the standardized method (20). Using this method, the FDP was cemented on the abutment, the FDP-abutment complex embedded in resin, the samples sectioned with a low-speed diamond sectioning saw, and the specimens examined using a stereomicroscope providing physical pictures for measuring. The method was meant for the study of marginal fit but can also be used for the study of internal fit. Even so, this method, as with the direct view technique, is considered to be out-dated as digital techniques are available.

The replica method is one of the most used methods for investigating the internal fit of fixed dental prostheses. It was first presented by McLean and von Fraunhofer in 1971 and, by November 2019, the article has been cited 493 times according to Web of Science Core Collection. A polyether material (Impregum, 3M ESPE) was found to be the best material for the replication of the cement space as it is similar to De Trey´s zinc phosphate cement in working time, setting time, and flow. The working and setting time of the two materials were found to be relatively similar, being about 3 and 5 minutes, respectively, for both materials. The film thickness was found to be 22 µm for polyether and 20 µm for zinc phosphate cement. Consistency testing gave an average disc diameter of 35 mm for polyether and 30 mm for zinc phosphate cement. They concluded that these two tests indicated that the flow properties of the two materials were comparable (21). The original procedure was described as 1) applying polyether on the intaglio of the FDP, 2) placing of the FDP on the abutment under finger pressure, 3) removal of the FDP and the cement layer analogue from the abutment, 4) replacing the abutment with resin to stabilize the cement layer analogue 5) removal of stabilized cement layer analogue from the FDP, and 6) further stabilization by embedding of the cement layer analogue in resin. The specimens were sectioned with a slitting wheel in a handpiece rotating at low speed. The surfaces were prepared for microscopic examination by grinding on 200 grit and 600 grit silicon carbide sandpapers. The specimens were examined under low magnification with a microscope and the width of the cement layer analogue was measured (21). Figure 2 illustrates the replica technique (29).

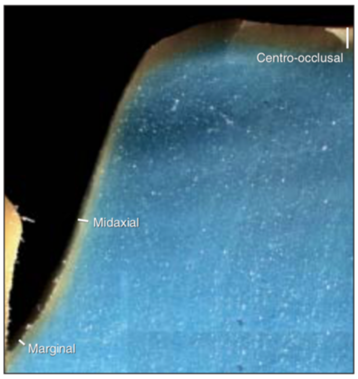

Figure 2. Example of replica technique. Yellow; cement layer analogue, blue; stabilizing silicone, black; FDP. From Tamim et al. (29) with permission

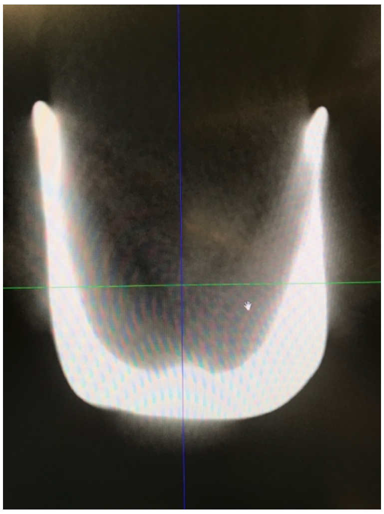

Figure 3. Example of cobalt-chromium test specimen on typodont abutment

Radiograph microtomography (µCT) uses x-rays to create cross-sections of a physical object that can be used to re-create a virtual model (3D model) without destroying the original specimen (Figure 3). The prefix micro (µ) indicates that the pixel sizes of the cross-sections are in the micrometre range. There are two setups of the µCT scanner; one in which the radiograph source and detector are stationary during the scan while the sample rotates, and one in which the sample is stationary and the radiograph source and detector are rotated. The latter setup is a typical *in vivo*-scanner used in scanning of e.g. peoples. The first µCT system was built by Jim Elliott in the early 1980s (30). In 2009, Pelekanos *et al.* used the method to study the marginal fit of In-Ceram alumina ceramic cores (31). Both the master die and the FDPs were made of glass-infiltrated alumina. A study by Borba *et al.* concluded that the µCT method seemed to be a reliable tool to evaluate the fit of dental restorations (32). In 2013 Contrepois *et al.* encouraged investigators to use this method in the measurement of marginal adaptation (26).

The user manual for SkyScan 1072 states that a "*radiography system produces two-dimensional shadow images of complete internal three-dimensional structures, but in a single two-dimensional shadow projection the depth information is completely mixed. Only a radiograph tomography system allows us to visualise and measure complete three-dimensional object structures without sample preparation or chemical fixation. Typically, the spatial resolution of conventional medical CT-scanners is in the range of 1-2.5 mm, which corresponds to 1-10 cubic mm voxel (volume element) size. Computerised radiograph microscopy and micro-tomography gives possibilities to improve the spatial resolution by seven to eight orders in the volume terms. The SkyScan 1072 allows us to reach a spatial resolution of 5 µm corresponding to near* $1x10^{-7}$ *cubic mm voxel size. As in the "macro" CT-scanners, the internal structure can be reconstructed and analysed fully non-destructively*" (33).

The triple-scan protocol was first described by Holst *et al.* (27) and later in studies by Matta *et al.* (34) and Svanborg *et al.* (35), amongst others. By November 2019 the study by Holst *et al.* (27) was cited 24 times according to Web of Science Core Collection. The triple-scan protocol is an evolution of the measurement technique presented by Luthardt *et al.* in 2004 (36). Holst *et al.* found this method to be effective for single units, but the registration process was very complex and limited to tooth-borne restorations (27). The test specimens are scanned in an industrial scanner. First the abutments are scanned and secondly the copings are placed on the abutments and scanned. Finally, the intaglios of the copings are scanned (Figure 4). The dedicated software ATOS Professional (GOM GmbH, Braunschweig, Germany) is used for merging the three scans. Another piece of software, GOM Inspect

(GOM GmbH, Braunschweig, Germany) is used for the investigation of the internal fit. In contrast to the replica method an unlimited number of digital sections can be made.

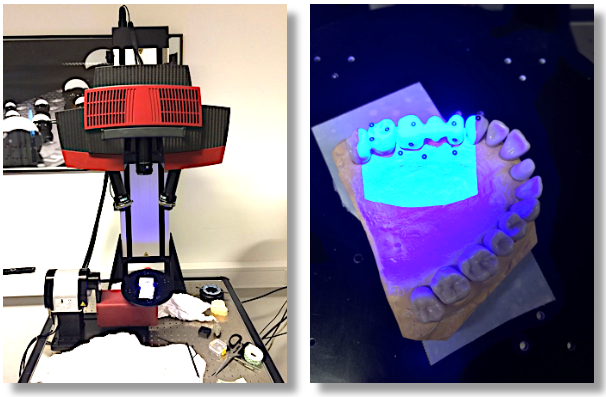

Figure 4. Scanning of specimens with ATOS III Triple Scan (left). Test specimen on master model (right)

The dual-scan protocol. The proposed term dual-scan protocol in Paper III is a modified version of the method described by Lee *et al.* (28). With this method, the prepared test specimens are scanned in a table-top scanner as used in a dental laboratory. In Paper III, this was done with the table-top scanner S600 ARTI (Zirkonzahn GmbH, Gais, Italy). First, the abutments are scanned. Secondly, a layer of silicone is deposited on the intaglios of the copings and the copings firmly placed on the prepared abutments. The copings are removed, leaving the silicone on the abutment as the cement layer analogue (Figure 5). The abutments with the cement analogue are scanned and the acquired digital files are exported from the scanner´s computer as STL-files and imported into a specific software i.e. GOM Inspect (GOM GmbH, Braunschweig, Germany) for analyses.

Figure 5. Master model with silicone as cement layer analogue

Materials for fixed dental prosthesis

Up until a few years ago the method and material of choice in Scandinavia when manufacturing copings for fixed dental prostheses (FDPs) was lost-wax and metal casting and gold alloys. Due to increased costs of gold and other precious elements, non-precious alloys have become popular. Cobalt-chromium (Co-Cr) is an alloy which in many ways can be compared to gold-based alloys. The physical properties are comparable; the modulus of elasticity even surpasses that of gold. As for casting of gold, the Co-Cr copings first have to be made as a wax pattern before investing and casting. Most often metal copings are subsequently layered with porcelain for a better aesthetic appearance. Because of new and different production techniques and higher demands for appealing results, other materials like zirconium dioxide and lithium disilicate have been taken into use. The copings made from zirconium dioxide and lithium disilicate can either be made monolithic, meaning that the surface is just stained and glazed after sintering, or made with the cut-back technique for subsequent layering of porcelain for a more aesthetic look.

In addition, the development of all-ceramic systems for dental restorations has been significant during the last four decades due to an increased demand for metal-free restorations. Slip-casting, heat-pressing, and computer-aided design/computer-aided manufacturing (CAD/CAM) are techniques new to dentistry which have been developed. All-ceramic materials have been improved to meet dental requirements, at the same time offering greater mechanical performance. All-ceramics contain a significantly greater amount of crystalline phase, from about 35 to about 99 volume%, as opposed to metal ceramics (37). The increased level of crystallinity provides improved mechanical properties through a number of mechanisms, i.e. crystalline reinforcement or stress-induced transformation. Higher crystallinity is associated with higher opacity, which most often is unwanted for ceramics used in dentistry. Zirconium dioxide such as 3 mol% yttria stabilized tetra zirconia polycrystal (3Y-TZP) offer excellent mechanical properties but are also the most opaque of all all-ceramic materials available (38). In any case, crystallinity is only one of several components giving a material its performance. Crystal size and geometry, modulus of elasticity, phase transformation and thermal expansion mismatch between crystal and glassy phase are other factors that play an important role in defining the mechanical expression of the ceramic.

The humid environment of the oral cavity may cause stress corrosion and failure in ceramic materials that contains a glassy phase (39). This is the case for the highly crystalline material 3Y-TZP which has been reported to degrade on a microstructural level in a humid environment at relatively low temperatures (40-42). It is accepted that tests have to be performed in a humid environment and under cyclic loading to provide correct information on the long-term performance of dental ceramics (43).

The dental porcelain crown originates from 1889 when Charles H. Land patented the "jacket" crown (44). In 1965 W. McLean and T.H. Hughes developed a new version of the "jacket" crown with an inner core of aluminous porcelain containing 40-50% alumina crystals (45). The content of alumina gave the new crown twice the strength of the traditional "jacket" crown.

The following sections describe the materials used in the present thesis in more detail. The test specimens made from the different materials are shown in Figure 6.

Figure 6. Test specimens used in this thesis. From left to right; zirconium dioxide, HIP zirconium dioxide, lithium disilicate reinforced glass ceramic, milled cobalt-chromium, sintered cobalt-chromium, and cast cobalt-chromium

Zirconium dioxide, also known as zirconia, is a ceramic material which contains zirconium and oxygen (ZrO_2). Zirconium is a chemical element with the symbol Zr and atomic number 40. The name is taken from the shimmering, grey-white metal zircon, which is the most important source of zirconium. The word zircon comes from the Persian word zargun, meaning "gold-coloured".

The characteristics and properties of zirconium dioxide (ZrO_2) are described in a review article by Manicone *et al.* as a crystalline dioxide of zirconium with mechanical properties comparable to those of metals and a colour similar to the colour of teeth (46). Zirconia crystals can be organized in three different phases; monoclinic phase (<1170°C), tetragonal phase (1170-2370°C), and cubic phase (>2370°C). These three phases are present in a common ZrO_2 crystal. By mixing ZrO_2 with other metallic oxides, such as MgO, CaO, or Y_2O_3, a higher degree of molecular stability can be obtained. ZrO_2 stabilized with 3 mol% (5.2 wt%) Y_2O_3 was shown to have the best mechanical properties for prosthetic restorations compared with other combinations (47). This combination is termed 3Y-TZP (3 yttria stabilized tetra zirconia polycrystal).

In 1975, Garvie *et al.* termed zirconia *ceramic steel* due to its mechanical properties (48). Its traction resistance can be up to 900-1200 MPa and its compression resistance is about 2000 MPa. The physical properties of zirconia can be modified by surface treatments. Every shift between the crystalline reticulations is because of a force on the zirconia surface, and this creates a volumetric change in the crystal where the stress is applied. When stress occurs on a surface of zirconia, cracking energy creates a transition from tetragonal phase to monoclinic phase. The crystalline change is followed by an expansion that seals the crack (49). Kosmac *et al.* found a lowered average strength and reliability of zirconium dioxide after grinding and at the same time they found that sandblasting improved the strength (50). Grinding of the inner surface significantly reduced the strength and reliability of Y-TZP zirconia compared with a polished control sample (51).

The colour appears during the final sintering. The final shade is strongly affected by the concentration of various metal oxides added and a satisfactory colouration is achieved with concentrations as low as 0.01 mol%. Also, the final sintering temperature has an effect on the colour achieved. The crystalline phases or mechanical properties of the final product appear not to be affected by colouration (52). To improve the monolithic zirconia with acceptable translucency, a transparent phase can be included in the final product. This can be achieved by using a higher yttria content to produce partially stabilized zirconia (PSZ) restorations; 4 mol% (4Y- PSZ) or 5 mol% (5Y-PSZ), with increased amounts of nonbirefringent (double refraction) c phase. Translucency is markedly improved, but toughness and strength are reduced as cubic zirconia does not go through stress-induced transformation (53).

Zirconium dioxide has been used in dentistry as root canal posts since 1989 (54) and as three-unit FDPs in the posterior region since 1998 (55).

Zirconium dioxide has most often been used as a core material covered with ceramic as veneering material, but most restorations in zirconium dioxide can be made monolithic without veneering. A monolithic restoration minimizes the problems of chipping and reduces the need for removal of more tooth substance than necessary. To achieve acceptable aesthetics the restorations are individually stained before the final sintering.

Figure 7. Lithium disilicate reinforced glass ceramic restorations; single crowns

Lithium disilicate reinforced glass ceramic is a glass ceramic based on SiO_2-Li_2O (Figure 7). Its properties have recently been reviewed by Shenoy and Shenoy (56). In this article lithium disilicate reinforced glass ceramic is described as a glass ceramic in which crystalline filler particles have been added to increase strength and improve the thermal expansion and contraction behaviour of the ceramic. The crystalline phase that forms is lithium disilicate ($Li_2Si_2O_5$). It makes up approximately 70% of the volume of the glass ceramic. Lithium disilicate has a rare microstructure as it contains randomly oriented interlocking plate-like crystals. For strength this is ideal, as the needle-like crystals cause cracks to deflect, branch, or blunt. By this the propagation of cracks through the material is halted by the lithium disilicate crystals, providing an increased flexural strength. When lithium orthophosphate (Li_3PO_4), a second crystalline phase is present the flexural strength is between 350 and 450 MPa. The glass ceramic is translucent due to the optical compatibility between the crystalline phase and the glassy matrix, which diminishes internal scattering of passing light. The processing temperature is 920°C. The grain sizes of the crystals of lithium metasilicate is between

0.2 µm and 1 µm, giving a flexural strength of 130 MPa to the material. Through the crystallization cycle there is a controlled growth of grain size to 0.5-5 µm (56).

Lithium disilicate reinforced glass ceramic (LDS) is an evolution from leucite reinforced glass-ceramic. The flexural strength of LDS is more than three times higher than leucite reinforced glass ceramic. Abrasiveness, chemical stability, and optical properties of all glass-ceramics fulfil the dental requirements. LDS can be used to fabricate 3-unit bridges up to the second premolar (57).

Due to patent rights, IvoclarVivadent has been the sole manufacturer of lithium disilicate (LDS) reinforced glass ceramic restorations for more than a decade under the name of IPS e.max Lithium Disilicate. Since a few years back, other manufacturers are offering products on the same basis (58). Prosthetic restorations in LDS can be made either by milling or by the lost-wax pressing technique. The flexural strength for IPS e.max is 360 MPa for milled LDS and 400 MPa for pressed LDS (59).

Cobalt-chromium is a metal alloy with a main content of cobalt (Co) and chromium (Cr). There are different compositions of Co-Cr alloys with regard to the content of cobalt, chromium, and additive elements. In a study by Kassapidou *et al.* (60) it was found that 1) cobalt-chromium alloys were more frequently used in FDPs than in fixed implant retained prostheses (FIPs), 2) dental laboratories use up to 35 different Co-Cr alloys in their production, 3) three different production techniques were used (casting, milling, and laser-sintering), and 4) casting was more common in the production of FDPs whereas milling and laser-sintering were more commonly used in the production of FIPs (60). The alloy used in the control group in Papers I-III contained 60.2% Co, 25.0% Cr, 6.2% W, 4.8% Mo, 2.9% Ga, < 1.0% Mn, and < 1.0% Si (61). Its physical properties are as follows: tensile strength 680 N/mm^2; Vickers hardness 280 HV10; ultimate elongation 14%; modulus of elasticity approximately 215,000 N/mm^2; density 8.6 g/cm^3; melting interval 1355-1430 °C; and casting temperature approximately 1500 °C.

Chromium alloys show high resistance to corrosion due to spontaneous formation of a protective film composed mostly of Cr_2O_3, and minor amounts of cobalt and other metal oxides (mostly molybdenum) on the surface. Cast, milled, and laser sintered Co-Cr alloys release low amounts of ions. There is no difference between the alloys when the specimens are exposed to an enriched bacteria milieu. All alloys are satisfactorily corrosion resistant and well suited for dental usage, although the cast alloy shows the greatest risk of corrosion under acidic conditions (62). In a review article by Levi *et al.* it was concluded that allergic reactions to metal alloys used in dentistry are well documented but that only a few articles focus on the correlation between FDPs and metal allergies (63).

Production techniques

Lost-wax and metal casting technique.

The lost-wax and metal casting technique as we know it today has been used since its introduction by Philbrook in 1896. It was for a long time the most widely used method of producing precious and non-precious alloy copings for FDPs. An impression of the prepared tooth is taken in an elastomeric material. A cast is created by pouring gypsum in the impression. On the cast the dental technician makes a wax pattern for the coping and invests the wax pattern. The wax is eliminated by placing the cuvette in an oven. Finally, the alloy is melted in the crucible formed in the investment, and cast by means of air pressure (64). After cooling the coping is removed from the investment. The coping can be layered with e.g. porcelain to achieve a higher degree of aesthetics. The alloy most often used has been gold alloy. Due to economic reasons gold alloy in some countries has been substituted by different chromium alloys. In Sweden, until 1999 the use of cobalt-chromium was only allowed for removable dental prostheses (RDPs) and temporary FDPs (65).

As presented earlier, the demand for metal-free FDPs has promoted the use of, among other materials, zirconium dioxide and lithium disilicate. The production methods used in the present studies are lost-wax and metal casting, milling, and laser sintering. The milling of zirconium dioxide is performed in the pre-sintered or the sintered stage. The terminology "pre-sintered" is used for frameworks milled before the final sintering and "sintered" is used for frameworks milled after the final sintering.

The computer-aided design/computer-aided manufacturing (CAD/CAM) technique.

This technique is based on a digital image of the patient´s teeth, digital construction of the FDP and digitally controlled production (66). The input commands are the results from a computerized design of the final product giving a so-called computer-aided design (CAD) file. This file is transformed into a program of machine control instructions to produce the product, and the production is then carried out. The automated control of machining tools (i.e. milling machine) by means of a computer is called computer numerical control (CNC) or simply numerical control (NC). A milling machine mills a piece of material (e.g. metal, PMMA, ceramic, or composite) to transform it to the desired specifications; a method called the subtractive technique. The milling machines join a motorized operated tool and most times a motorized operated platform. They are both operated by a computer, in accordance with detailed input commands. Other options are additive techniques like sintering of alloys and 3D printing of resin-based materials also based upon computerized input commands (67).

The French dentist Dr. François Duret is considered to be the pioneer of dental CAD/CAM. In 1973, he wrote a DDS thesis which described the idea of digital intraoral impression and the digital production of a fixed dental prosthesis. In 1983 he filed a patent based on his previous thesis. At the 1985

Association Dentaire de France´s meeting in Paris he prepared and fitted a single crown FDP on a patient. The session was done live and the courageous patient was his wife (68).

The German dentist Dr. Werner Mörmann, and electrical engineer Dr. Marco Brandestini, were second in line for CAD/CAM. Dr. Mörmann had seen how composite resin fillings shrunk during polymerization and hypothesized that adhesively cemented inlays made of tooth coloured material could solve the problem. First, he wondered if a prepared cavity in a tooth could be digitized by ultrasound. Dr. Brandestini, a specialist working on blood-flow ultrasound scanners, ruled out the ultrasound method because the wavelength was too large. Instead he came up with the idea to do it optically. In 1983, together with Siemens AG (now Dentsply Sirona), Mörmann and Brandestini launched the CEREC 1 unit. They described the technique in this way: "*The idea was to project a grid of parallel stripes under a parallax angle onto the preparation according to the known principle of triangulation and to acquire the depth-dependent shift of the lines with an area sensor (that is, a charge-coupled device (CCD) video chip).*" They called the operation of taking pictures of the prepared teeth and its surroundings with a camera in hand piece, performed by the dentist, for an "*optical impression*". On 19 September 1985, the first CEREC chairside treatment took place in the University of Zurich Dental School. The material used was Vita Mark I feldspatic ceramic (Vita Zahnfabrik) (69). The evolution of the CAD-part took a major leap in 2003 with the introduction of the three-dimensional version of the CEREC software as it was much more illustrative than previous versions and made the handling of the system more intuitive and easy (69).

Due to the increasing cost of gold in the beginning of the 1980s, cobalt-chromium and nickel-chromium alloys were used as an alternative. In Northern Europe allergies towards the alloy were reported and a shift towards titanium was put forward (70). The casting of titanium was difficult at that time and in 1989, Dr. Matts Andersson described a new combined technique for fabrication of titanium crowns. It involved machine duplication and spark erosion. The technique is now known as the Procera system. The die is physically read with the tip of a probe. With the CAD software the outer anatomy of the coping is designed and a milling machine mills the object from a blank of titanium. The shape of the intaglio of the coping is spark eroded using a carbon electrode. Two to three electrodes had to be used for the production of one titanium coping. The copings would later be veneered with acrylic resin or porcelain (71).

Sveriges Tandteknikerförbund has conducted surveys amongst their members, and report that approximately 90% of the work done has in some way used elements of CAD/CAM. The corresponding numbers for other European countries was anticipated to be somewhat lower. (SAHLIN, O, Chairman of Sveriges Tandteknikerförbund, 2019, personal communication).

Computer-aided design.

The process by which digital information from a scanner is processed by software in a personal computer is termed computer-aided design (72). The CAD software imports the file from the scanner and by algorithms transforms the information into visual information. The designer, usually a dental technician, digitally constructs the desired object. The output is in the form of electronic files for the production by e.g. laser sintering or milling. CAD software is used to increase the productivity of the designer, improve the quality of design, enhance communications through documentation, and to create a database for manufacturing.

Computer-aided manufacturing; subtractive technique (milling).

One of the tested manufacturing methods was milling. It is a subtractive method where material is successively removed by milling in order to form the desired object. From the CAD software a digital file is sent to the milling machine. The file contains a plan on how to grind a prosthetic restoration out of a solid block. It is very important to maintain the strength of the blank to avoid its breakage during milling. The intaglio and the margins are milled before the outer contours are formed and finally, the restoration is separated from the blank. The paths of the tools the milling machine have to use during the fabrication process must be calculated. The relative orientation of the tools and the blank must also be optimized. The milling machine has to use adequate tools to contour each area of the restoration´s shape. Autonomously, the milling machine inspects the wear of the tools and changes them when the tolerance has been reached. It is important that the milling machine is designed to avoid over-heating during milling. It is also important that the milling machine saves a log of what has been produced. The coping can be milled from a blank of different materials, e.g. cobalt-chromium, zirconia, wax, poly(methyl methacrylate) (PMMA), composite resin, polyether ether ketone (PEEK), or gypsum. Depending on the material used the milling can be done wet or dry. The blocks are industrially made under optimal conditions. Large constructions can be made in one piece. This is an advantage because soldering of minor parts to a larger part gives a weaker product than a homogenous mono-block. The drill can be positioned in up to seven axes relative to the blank. In this way, the bur can reach almost every small corner. In cases where part of the intaglio of the coping is to be milled to a smaller size than the diameter of the drill, or the drill´s accessibility is restricted, the manufacturing process has to compensate for this by performing drill compensation (Figure 8) (73).

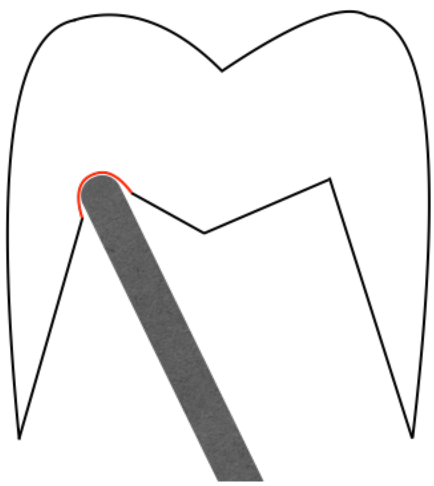

Figure 8. Illustration of drill compensation. The drill has to remove more substance than necessary to reach the outermost part because of its larger dimension than the desired shape

Prosthetic restorations of zirconium dioxide can be “hard-machined” or “soft-machined”. The "hard-machined" restorations are milled from a fully sintered blank. In the book "Clinical Applications of Digital Dental Technology" from 2015 hard milling is only mentioned in a historical context as the method requires heavy duty machinery, it is claimed to induce flaws and cracks in the material, and the method leads to comprehensive wear of tools (74). The "soft-machined" restorations are milled from a partially sintered "green" or partially crystallized blank, which is fully sintered or crystallized, respectively, after milling. To compensate for the subsequent shrinking during sintering, the "soft-machined" restorations are milled 20-25% oversized (75). The crystallization of partially crystallized blanks is not accompanied by shrinkage (74). As the materials are relatively soft the production time and the consumption of tools are reduced compared to the milling of sintered blocks. As with the majority of all work with dental applications it is most important that the dental technician respects the manufacturers´ instructions.

Computer-aided manufacturing; additive technique (sintering).

Another tested manufacturing method was direct laser metal sintering (DLMS). The DLMS method resembles the selective laser sintering (SLS) method (76). The difference between the DLMS and SLS methods is that during DLMS the metal is sintered while during SLS the metal is melted and fused (77). Both techniques deliver a metal construction with a crystal structure and the risk of building in porosities. DLMS is an additive method where up to 20 µm thick layers of metal powder are laser sintered to successively build a prosthetic restoration. In our studies, the metal used was cobalt-chromium (Co-Cr). Sintering must be done in a CO_2 atmosphere for Co-Cr metal powder and argon atmosphere for titanium metal powder (78). The sintered copings need more post-processing manual labour than the milled copings. An advantage of the sintering method is that more copings can be manufactured at the same time compared to the milling method. Another advantage is that the material waste is just a fraction compared to the milling method where more than 90% of the block is waste after milling (67, 79). When sintered copings are used in implant supported restorations the contact area to the implant/abutment is milled to get a smooth surface as sintering leaves a rougher surface compared to milling.

Null-hypothesis of the thesis

This thesis evaluates the internal fit of fixed dental prostheses produced by conventional and digital techniques. The null-hypothesis is that FDPs made by new production methods and materials have the same internal fit as FDPs made by cast cobalt-chromium.

5. Aim

The primary aim of the thesis is

- to evaluate the internal fit of fixed dental prostheses

The secondary aims are

- to compare the internal fit of single crowns of different materials produced by recent digital techniques and the older lost-wax and metal casting technique
- to compare the internal fit of three-unit fixed dental prostheses of different materials produced by recent digital techniques and the older lost-wax and metal casting technique
- to use and compare two digital methods (the triple-scan and the dual-scan methods) for the investigation of internal fit

6. Materials and methods

The design of the Papers I to III in this thesis is a comparative quantitative analysis. In all of the studies, the internal cement space of five different types of computer-aided designed and computer-aided manufactured (CAD/CAM) fixed dental prostheses (FDPs) was compared to FDPs manufactured by the lost-wax and metal casting technique.

A model of the maxilla with teeth from the right third molar to the left third molar was made with KaVo typodont teeth (KaVo Dental, Biberach/Riß, Germany) embedded in Type IV gypsum. The left central incisor was prepared by one of the authors (BED) with a diamond rotary cutting instrument (ISO 290 014; Horico, Berlin, Germany) for a single crown and the first premolar and molar in the first quadrant were prepared for a three-unit FDP. The second premolar was removed. (Figure 9).

Figure 9. Prepared typodont teeth embedded in gypsum

A digital impression was made of the typodont model with an intraoral scanner (Trios, 3Shape; Copenhagen, Denmark; serial number t1402c12012b, software build: 1.3.3.1 CL206342). The stereolithography (STL) file was sent to a dental technician for CAD/CAM. From the single STL file, five different designs were made to fulfil the manufacturers´ recommendations for producing the frameworks for the following types of restorations: 1) pre-sintered zirconia (Dental Direkt, Spenge, Germany), 2) hot isostatic pressed yttria-tetragonal polycrystal ceramic (Denzir, Skellefteå, Sweden), 3) lithium disilicate reinforced glass ceramic (IvoclarVivadent, Schaan, Liechtenstein), 4) milled cobalt-chromium (Eisenbacher Dentalwaren, Wörth am Main, Germany), and 5) laser-sintered cobalt-chromium (Dentware, Kristianstad, Sweden). Three crowns and three three-unit FDPs of each type were produced based on the same STL file to avoid differences related to the scanning procedure. Three impressions in polyvinyl siloxane (Imprint 4, 3M ESPE, St Paul, MN, USA) were taken and sent to a dental technician. The dental technician produced three cobalt-chromium (Wirobond 280, Bego, Bremen, Germany) copings for both single crowns and for three-unit FDPs by the lost-wax and metal casting technique. The definitive casts were spaced according to standard laboratory procedure. The cast copings were used as a control group. The restorations were not veneered with porcelain. A total of 36 frameworks were produced. It was specified that the intaglios of the frameworks were to be treated as if they were to be cemented (Table 1).

Table 1. Listing of materials and settings used in the production of the frameworks

				Cement space settings in µm	
Group	**Name**	**Manufacturer**	**Laboratory**	**Marginal**	**Internal**
Zir[1]	DD Bio ZW iso Zirkonoxid, 3Y-TZP	Dental Direkt	Tannlab	30	70
HIP-Zir[2]	Denzir	Denzir	Denzir	15	50
LiSi[3]	e.max CAD	Ivoclar Vivadent	Tannlab	30	60
M-Co-Cr[4]	ED Kera-Disc CoCr	Eisenbacher Dentalwaren	DenTech/ Østvold Dental	50	90
Ls-Co-Cr[5]	Dentware CoCr	Dentware	Dentware	55	80
C-Co-Cr[6]	Wirobond 280	Bego	Tannlab	0*	20*

*Thickness of one coat of Kerr Classic Cement Spacer is 20 µm according to manufacturer. Spacing started 0.5 mm from preparation margin

[1]Zir; milled pre-sintered zirconium dioxide

[2]HIP-Zir; milled hot isostatic pressed (HIP) zirconium dioxide

[3]LiSi; milled lithium disilicate reinforced glass ceramic

[4]M-Co-Cr; milled cobalt-chromium alloy

[5]Ls-Co-Cr; laser sintered cobalt-chromium alloy

[6]C-Co-Cr; cast cobalt-chromium alloy

In Papers I and II the master model and the frameworks were scanned (ATOS III Triple-scan, GOM mbH, Braunschweig, Germany) using the triple-scan method described by Holst *et al.* (27). The accuracy of the scanner was measured by the manufacturer (GOM mbH, Braunschweig, Germany) to be 4 µm. Identification markers were applied to the coping and master model for later merging of the digital files. Scanning was performed in three steps; scanning of the master model, scanning of the coping on the master model, and scanning of the intaglio of the coping. To obtain a scan of the highly reflective intaglio, the coping had to be sprayed with titanium dioxide. The second and third scans were used to position the coping on the master model. The corresponding three digital files were superimposed in ATOS Professional software (GOM mbH, Braunschweig, Germany) using the best fit algorithm. The results were analysed with GOM Inspect (GOM mbH, Braunschweig, Germany).

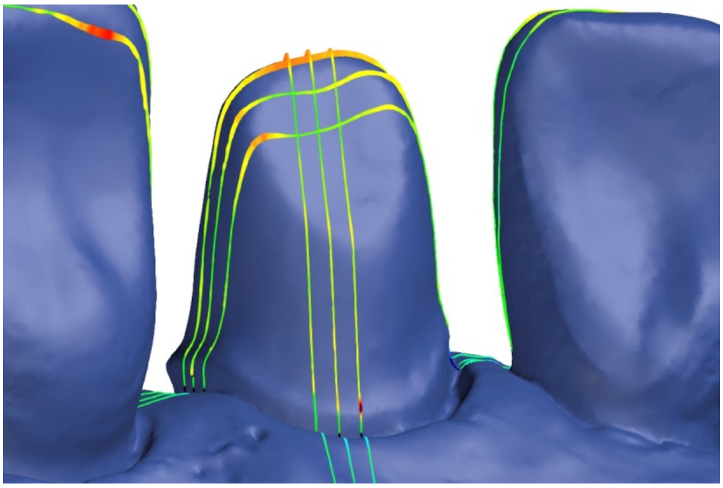

Figure 10. Sample of symmetrical planes in mesio-distal and palato-gingival directions

The space between the restoration and the abutment can be interpreted as the restoration´s adaptation or fit. In Papers I and II, marginal fit was considered as the distance from the preparation margin and 0.5 mm in the occlusal direction, while the internal fit was measured on the distance occlusal to the marginal fit. In Papers II and III the marginal band defined as a band being 0.5-1.0 mm from the preparation margin was used to analyse marginal fit.

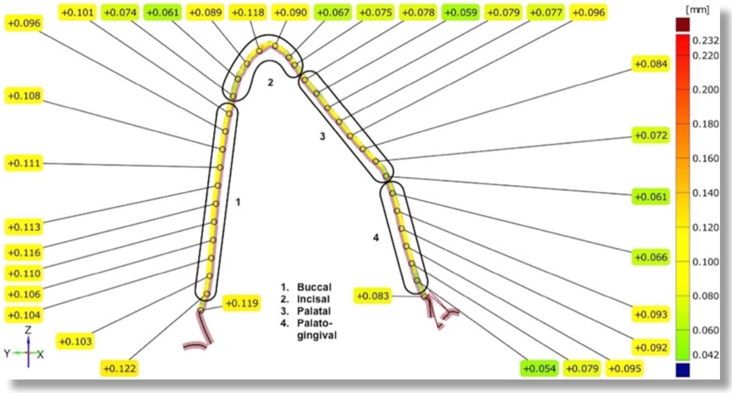

Figure 11a. Sample of measuring points in the bucco-palatal section

One point on each of the mesial, distal, buccal, and palato-gingival surfaces was chosen in the GOM Inspect software for the construction of fitting planes. A section was defined as the symmetrical plane between the fitting planes on the buccal and palato-gingival and the mesial and distal planes (Figure 10). The thickness of the internal cement space was recorded in the bucco-palatal and in the mesio-distal direction. The nearest measuring point to the preparation margin was set at 0.5 mm. The bucco-palatal section was divided into four subsections: buccal, incisal, palatal, and palato-gingival (Figure 11a). The mesio-distal section was divided into five subsections: mesial, mesio-occlusal, occlusal, disto-occlusal, and distal (Figure 11b).

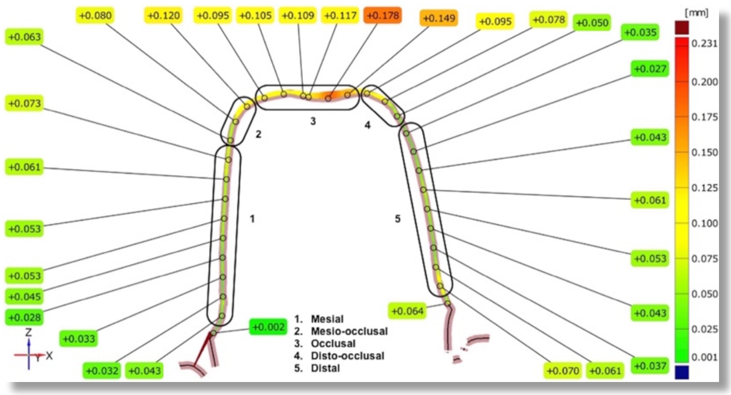

Figure 11b. Sample of measuring points in the mesio-distal section

In Paper I the average area of the abutments scanned was 106 mm^2 and the average total number of points measured was approximately 197 000 (Figure 11c). Cut-off distance was set to 1.0 mm, implying that measurements exceeding 1.0 mm were considered outliers.

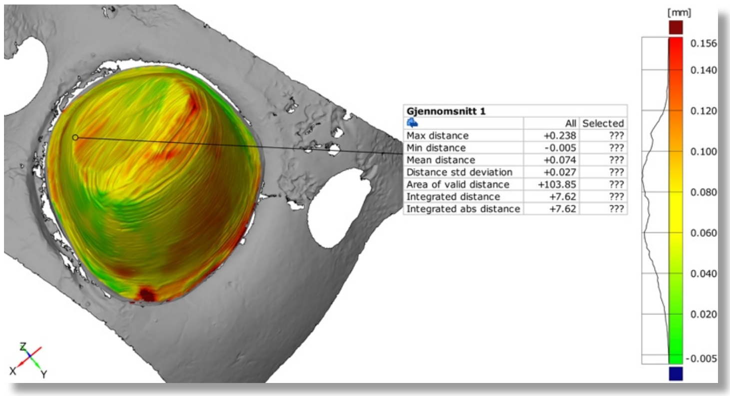

Figure 11c. Illustration of single upper central incisor abutment used for determination of maximum marginal discrepancy and cement space and average marginal discrepancy and cement space

In Paper III the master model and the copings were scanned with a table-top scanner (S600 ARTI, Zirkonzahn GmbH, Gais, Italy) using its dedicated software (Zirkonzahn.Scan, Zirkonzahn GmbH, Gais, Italy). The manufacturer stated that the scanner had a precision of <10 µm (80). First the master model was scanned. A separating agent (YetiLube, YETI Dentalprodukte GmbH, Engen, Germany) was applied on the intaglios of the test specimens to prevent the silicone from adhering (81). Secondly, the intaglio of the coping was filled with light-body silicone (FitChecker™ Advanced Blue, GC Europe N.V., Leuven, The Netherlands) (82). The coping was placed on the prepared tooth of the master model with a firm finger pressure as if it was to be cemented with a water-based type of cement. The coping was removed from the master model leaving the silicone on the prepared tooth. The silicone layer representing the cement analogue was sprayed with Finoscan (FINO GmbH, Bad Bocklet, Germany) (83) to improve the contrast prior to scanning.

The next step was to scan the master model with the silicone as the cement analogue on the prepared tooth. In the Zirkonzahn.Modellier software (Zirkonzahn GmbH, Gais, Italy) the digital files of each of the 18 scans were respectively superimposed on the scan of the master model/patient using the best fit algorithm. The files were exported in STL-format and imported in the GOM Inspect software. The marginal 0.5 mm was excluded due to the high magnification which made it difficult to distinguish the preparation´s and coping´s margins. Measuring points were decided as in the studies with the triple-scan protocol. Measurements exceeding 1.0 mm were considered outliers. The statistical analyses were similar to those in Papers I and II.

In all studies, the statistically significant difference among groups was evaluated using a spreadsheet (Excel 2011 for Mac v14.6.2; Microsoft Corp, Redmond, WA, USA) and Student *t*-test. The statistically significant level was set to $p<.05$.

7. Results

The results of Paper I are shown in Tables 2 and 3. The measurements in the bucco-palatal direction showed that the cement space was wider in the incisal and palatal sections than in the buccal and palato-gingival sections (Table 2).

Table 2. Cement space in different subsections of bucco-palatal direction, average values (±standard deviation) in µm in Paper I. All CAD/CAM specimens had statistically significant larger cement spaces compared with C-Co-Cr group except palato-gingival subsection and two groups of buccal section (marked *). No statistical difference among other groups

	Group					
Subsection	**Zir**	**HIP-Zir**	**LiSi**	**M-Co-Cr**	**LS-Co-Cr**	**C-Co-Cr**
Buccal	36 (9)	66 (20*)	94 (32)	45 (7*)	88 (18)	63 (33)
Incisal	202 (113)	140 (70)	125 (56)	234 (124	155 (50)	72 (27)
Palatal	171 (25)	203 (27)	102 (33)	231 (39)	97 (11)	65 (13)
Palato-gingival	57 (14*)	69 (19*)	68 (25*)	64 (18*)	57 (10*)	65 (17)

In the mesio-distal direction, the cement space was widest at the incisal section (Table 3).

Table 3. Cement space in different subsections of mesio-distal direction, average values, (±standard deviation) in µm in Paper I. All CAD/CAM specimens had statistically significant larger cement spaces compared with C-Co-Cr group. No statistical difference among other groups

	Group					
Subsection	**Zir**	**HIP-Zir**	**LiSi**	**M-Co-Cr**	**LS-Co-Cr**	**C-Co-Cr**
Mesial	70 (12)	52 (11)	65 (24)	68 (27)	104 (15)	41 (14)
Mesio-occlusal	259 (157)	188 (109)	149 (74)	297 (127)	148 (29)	82 (26)
Occlusal	485 (141)	355 (60)	262 (133)	595 (96)	221 (35)	102 (36)
Disto-occlusal	183 (88)	199 (88)	227 (95)	277 (122)	166 (50)	100 (34)
Distal	82 (17)	90 (19)	92 (19)	76 (34)	47 (13)	42 (19)

Comparing the CAD/CAM groups with the C-Co-Cr group, all measurements except for the palato-gingival sections and the buccal sections for the HIP-Zir and M-Co-Cr groups were statistically significantly greater. All internal sampling points for the bucco-palatal and mesio-distal sections are summarized in Table 4, which shows that all restorations made with the CAD/CAM technique had a larger cement space than the restorations in the control group made with the lost-wax and metal casting technique. The differences were statistically significant.

Table 4. Evaluation of entire internal fit section (margins excluded) for all internal sampling points in bucco-palatal and mesio-distal sections in Paper I. Average values (±standard deviation) in µm. Totally, 522 points per group in bucco-palatal and mesio-distal section were analysed. All specimens had statistically significant larger cement spaces than C-Co-Cr. No statistical difference among other groups

Specimen	**Bucco-palatal**	**Mesio-distal**
Zir	105 (89)	165 (164)
HIP-Zir	113 (68)	138 (115)
LiSi	97 (41)	128 (97)
M-Co-Cr	130 (107)	193 (199)
LS-Co-Cr	97 (41)	114 (65)
C-Co-Cr	66 (25)	61 (35)

An analysis of approximately 106 mm^2 and 197 000 points per abutment/crown in the GOM Inspect software (without the possibility of statistical calculation) revealed the average maximum cement space and the average space of the 3 specimens in each material group (Table 5). The highest average maximum space of 776 µm was found in the Zir-group, and the smallest average maximum space in the control group C-Co-Cr-group with 193 µm.

Table 5. Marginal discrepancy and cement space (±standard deviation) in µm based on measurements on entire prepared abutment and intaglio of crown; 106 mm^2 and 197 000 points per abutment/crown in Paper I. Data from GOM Inspect. †Average of 3 specimens in each group

Group	**Maximum marginal discrepancy and cement space†**	**Average marginal discrepancy and cement space†**
Zir	776	78 (65)
HIP-Zir	325	81 (56)
LiSi	521	76 (47)
M-Co-Cr	465	90 (78)
LS-Co-Cr	286	82 (37)
C-Co-Cr	193	58 (23)

In Paper II the fit was evaluated for both single abutments and three-unit FDPs. The results are shown in tables 6 to 11. The average internal cement space varied between 50 µm and 300 µm. Insignificant differences of internal fit were observed between the CAD/CAM manufactured FDPs, and none of the CAD/CAM manufactured FDPs had internal cement spaces that were statistically significantly different from those of the control FDPs. For all FDPs, the cement space at a marginal band 0.5-1.0 mm from the preparation margin was less than 100 µm. The milled cobalt-chromium FDP appeared to have the closest fit. The cement space of FDPs produced using the CAD/CAM technique was similar to that of FDPs produced using the conventional lost-wax and metal casting technique.

Table 6. Average (±standard deviation) cement space in µm of the marginal band 0.5-1.0 mm from preparation margin in Paper II. Average of 72 measuring points per test group; 18 mesial, 18 distal, 18 buccal, and 18 palatal

	Marginal band width					
Tooth	**Zir**	**HIP-Zir**	**LiSi**	**M-Co-Cr**	**Ls-Co-Cr**	**C-Co-Cr**
16	59 (29)	57 (21)	89 (29)	50 (16)	81 (33)	87 (53)
14	58 (24)	56 (24)	86 (24)	52 (18)	74 (23)	87 (63)

Table 7. Average (±standard deviation) width in µm of the cement space in different subsections of the bucco-palatal aspect of the first molar in Paper II

	Average width of first molar in bucco-palatal section					
Subsection	**Zir**	**HIP-Zir**	**LiSi**	**M-Co-Cr**	**Ls-Co-Cr**	**C-Co-Cr**
Buccal	65 (24)	75 (14)	113 (13)	87 (10)	73 (15)	50 (17)
Bucco-occlusal	215 (130)	154 (46)	153 (60)	297 (128)	126 (56)	134 (94)
Occlusal	96 (41)	100 (25)	251 (31)	167 (21)	207 (24)	198 (133)
Palato-occlusal	253 (108)	210 (57)	195 (48)	330 (146)	180 (56)	144 (94)
Palatal	87 (28)	71 (24)	71 (24)	41 (15)	87 (13)	70 (19)
Average	109 (81)[3]	99 (50)[3,4,5]	151 (79)[1,2,6]	135 (110)[2]	129 (64)[2]	121 (102)[3]

[1] Estimate statistically significantly different from that of Zir

[2] Estimate statistically significantly different from that of HIP-Zir

[3] Estimate statistically significantly different from that of LiSi

[4] Estimate statistically significantly different from that of M-Co-Cr

[5] Estimate statistically significantly different from that of Ls-Co-Cr

[6] Estimate statistically significantly different from that of C-Co-Cr

Table 8. Average (±standard deviation) width in µm of the cement space in different subsections of the bucco-palatal aspect of the first premolar in Paper II

	Average width of first premolar in bucco-palatal section					
Subsection	**Zir**	**HIP-Zir**	**LiSi**	**M-Co-Cr**	**Ls-Co-Cr**	**C-Co-Cr**
Buccal	71 (28)	72 (37)	101 (33)	83 (38)	36 (14)	66 (29)
Bucco-occlusal	188 (82)	146 (38)	140 (82)	260 (65)	134 (48)	117 (83)
Occlusal	112 (31)	100 (32)	254 (41)	164 (39)	188 (42)	154 (113)
Palato-occlusal	116 (61)	73 (40)	195 (60)	168 (39)	100 (50)	131 (98)
Palatal	52 (17)	46 (18)	54 (26)	30 (15)	50 (18)	105 (50)
Average	89 (54)[3,4]	78 (42)[1,3,4,6]	133 (85)[1,2,4,5,6]	110 (79)[1,2,5]	87 (67)[3,4]	106 (77)[2,3]

[1] Estimate statistically significantly different from that of Zir

[2] Estimate statistically significantly different from that of HIP-Zir

[3] Estimate statistically significantly different from that of LiSi

[4] Estimate statistically significantly different from that of M-Co-Cr

[5] Estimate statistically significantly different from that of Ls-Co-Cr

[6] Estimate statistically significantly different from that of C-Co-Cr

Table 9. Average (±standard deviation) width in µm of the cement space in different subsections of the mesio-distal aspect of the first molar in Paper II

	Average width of first molar in mesio-distal section					
Subsection	**Zir**	**HIP-Zir**	**LiSi**	**M-Co-Cr**	**Ls-Co-Cr**	**C-Co-Cr**
Distal	71 (23)	52 (12)	54 (10)	58 (10)	57 (20)	38 (26)
Disto-occlusal	189 (80)	199 (65)	157 (89)	171 (79)	183 (43)	160 (111)
Occlusal	111 (34)	112 (25)	266 (27)	170 (11)	199 (28)	235 (153)
Mesio-occlusal	162 (52)	143 (25)	179 (61)	199 (36)	200 (28)	174 (104)
Mesial	80 (29)	80 (21)	139 (32)	52 (15)	141 (22)	118 (36)
Average	105 (56)[3,5,6]	99 (53)[3,5,6]	154 (87)[1,2,4]	110 (68)[3,5]	142 (63)[1,2,4]	136 (117)[1,2]

[1] Estimate statistically significantly different from that of Zir

[2] Estimate statistically significantly different from that of HIP-Zir

[3] Estimate statistically significantly different from that of LiSi

[4] Estimate statistically significantly different from that of M-Co-Cr

[5] Estimate statistically significantly different from that of Ls-Co-Cr

[6] Estimate statistically significantly different from that of C-Co-Cr

Table 10. Average (±standard deviation) width in µm of the cement space in different subsections of the mesio-distal aspect of the first premolar in Paper II

	Average width of first premolar in mesio-distal section					
Subsection	**Zir**	**HIP-Zir**	**LiSi**	**M-Co-Cr**	**Ls-Co-Cr**	**C-Co-Cr**
Distal	56 (15)	55 (11)	66 (12)	39 (7)	08 (23)	106 (38)
Disto-occlusal	165 (73)	157 (82)	176 (65)	163 (79)	194 (56)	155 (93)
Occlusal	233 (61)	202 (59)	256 (18)	269 (41)	204 (46)	161 (131)
Mesio-occlusal	194 (121)	165 (73)	161 (51)	196 (121)	126 (40)	128 (118)
Mesial	87 (23)	91 (20)	54 (34)	78 (10)	112 (18)	52 (20)
Average	122 (88)	114 (72)	115(80)	118 (98)	131 (55)	109 (84)[1]

[1] Estimate statistically significantly different from that of Ls-Co-Cr

Table 11. Results of pooled cement space measurements in µm (±standard deviation) for each test group compared to cement space settings given by the manufacturers in Paper II

First premolar	**Zir**	**HIP-Zir**	**LiSi**	**M-Co-Cr**	**Ls-Co-Cr**	**C-Co-Cr**
Average all sampling points (n=171)	103 (72)	93 (59)	122 (85)	115 (86)	107 (66)	107 (80)
Manufacturer´s setting	70	50	60	90	80	20
Average deviation from manufacturer´s setting	33	43	62	25	27	87
Deviation from manufacturer´s setting	47%	86%	104%	28%	33%	436%

First molar	**Zir**	**HIP-Zir**	**LiSi**	**M-Co-Cr**	**Ls-Co-Cr**	**C-Co-Cr**
Average all sampling points (n=192)	107 (70)	99 (51)	150 (84)	126 (93)	135 (66)	128 (97)
Manufacturer´s setting	70	50	60	90	80	20
Average deviation from manufacturer´s setting	37	49	90	36	43	98
Deviation from manufacturer´s setting	53%	98%	150%	40%	54%	492%

Three-unit bridge	**Zir**	**HIP-Zir**	**LiSi**	**M-Co-Cr**	**Ls-Co-Cr**	**C-Co-Cr**
Average all sampling points (n=363)	105 (71)	98 (55)	140 (85)	122 (90)	123 (66)	118 (97)
Manufacturer´s setting	70	50	60	90	80	20
Average deviation from manufacturer´s setting	35	48	80	32	43	98
Deviation from manufacturer´s setting	50%	96%	134%	36%	54%	492%

In Paper III the digital files were analysed in GOM Inspect software as described in Papers I and II. Additional sections were made and the total number of measuring points per specimen was 84 in the mesial-distal direction and 93 in the buccal-palatal direction. The number of measuring points in the marginal band was 24 per specimen. The results showed that the internal fit for copings made with the lost-wax and metal casting technique was tighter than for all other specimens tested (Figure 11).

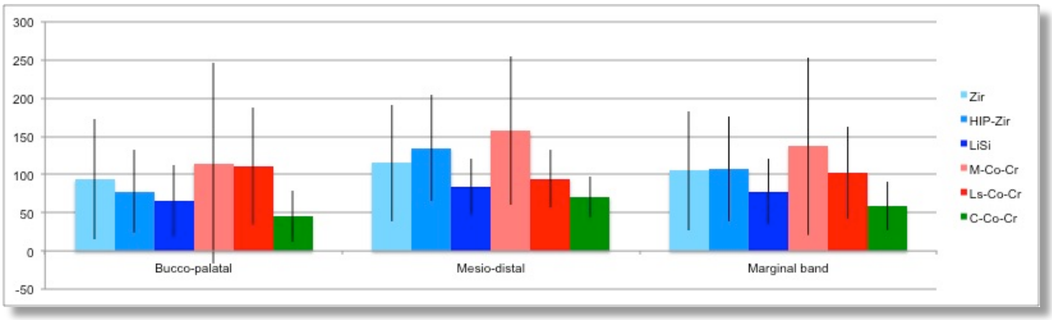

Figure 11. Pooled results for the bucco-palatal section, mesio-distal section, and marginal band studied with the dual-scan method

Comparing the manufacturer´s settings for production of copings showed that the percentage deviation was quite substantial for cast cobalt-chromium (Figure 12).

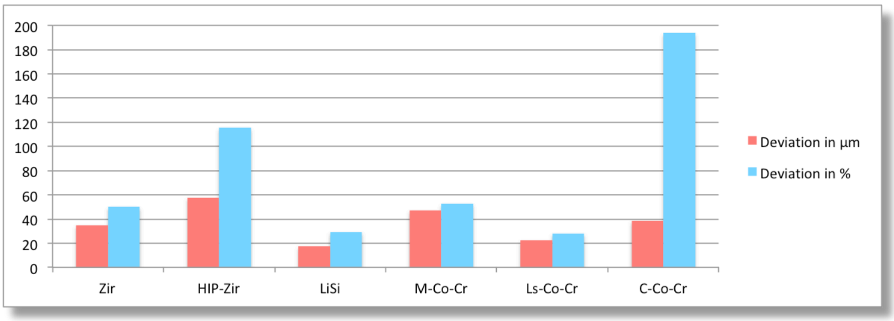

Figure 12. Deviation from settings in µm and percent.
The numeric values on the y-axis represent both µm and percent

8. Discussion

The primary aim of the study was to investigate the internal fit of fixed dental prostheses (FDPs). The secondary aims were: i) to compare the internal fit of single crown FDPs of different materials produced by recent digital techniques and the older lost-wax and metal casting technique, ii) to compare the internal fit of three-unit FDPs of different materials produced by recent digital techniques and the older lost-wax and metal casting technique, and iii) to compare two digital methods (the triple-scan and the dual-scan methods) for the investigation of internal fit.

The most widely used method of investigating the internal fit is the replica method. In a recent study by Falk *et al.*, it was confirmed that the replica method was reliable for the investigation of internal fit and marginal discrepancy of FDPs (84). Still, the method has several limitations due to the mechanical properties of the materials used; i.e. the stabilizing and the sectioning of the cement layer analogue and the decision on where to set the reference points. Because of the two aforementioned limitations, and the vast opportunities the new digital techniques can offer, it was timely to conduct investigations with the double-scan and triple-scan methods.

Evaluation of methods for examination of internal fit

1. Triple-scan method versus replica method. As the triple-scan method described by Holst *et al.* is a relatively new method for the investigation of internal fit of fixed dental prostheses it has by November 2019 only 24 citations according to Web of Science Core Collection (27). The replica method was described by McLean and von Fraunhofer 40 years earlier and has 493 citations (21). In 2012, Matta *et al.* concluded that a virtual gap analysis based on the triple-scan protocol provided additional quantitative measurements of restoration quality and that a non-destructive computer-aided measurement technique for component testing showed great potential for use in future investigations (34). A similar conclusion was drawn by Boitelle *et al.* after comparing the triple-scan method to the replica method (85). Anadioti *et al.* investigated the marginal fit of pressed and CAD/CAM manufactured lithium disilicate single crown FDPs made from digital and conventional impressions using the triple-scan protocol (86). They defined 2D measurements corresponding to the mesio-distal and bucco-lingual sections in Papers I-III and 3D measurements corresponding to the marginal band defined in the same studies. The conclusion by Anadioti *et al.* was that "*the fact that the 2D and 3D measurements resulted in the same conclusion validated the reliability of the software and the measurement protocol used*" (86). A major advantage with the triple-scan method is the possibility to investigate an infinite number of points. With the triple-scan and dual-scan methods one can digitally design and investigate additional sections of the same virtual replica of the cement layer. It is also possible to investigate multiple parallel sections summed up to mimic an area. The number of sections is limited as it is required that the sections are perpendicular to the surface. Measuring the internal fit of two or more parallel sections at more than two points per section gives an estimate of the volume.

2. Triple-scan method versus direct view method. As shown by Nawafleh *et al.* the direct view method is the most used method for the investigation of the marginal fit of FDPs (18). The method was first described in the article "Preparation design and margin distortion in porcelain-fused-to-metal restorations" by Shillingburg *et al.* (19). This article has by November 2019 been cited 101 times in Web of Science Core Collection. Compared to the newer and more sophisticated digital methods such as the triple-scan method, the direct view method seems limited as it can only investigate the marginal fit. The marginal fit is of great importance for the longevity of a FDP in order to reduce the risk of recurrent caries. The ability to visually inspect the marginal gap is a prerequisite for the direct view method.

4. Triple-scan method versus µCT method. Using the µCT method, Pimenta *et al.* investigated the marginal and internal fit of FPDs manufactured by milled zirconium dioxide, pressed lithium disilicate, and by nickel-chromium alloy and the lost-wax and metal casting technique (25). The results showed that cast nickel-chromium exhibited the best marginal fit and the pressed lithium disilicate the best internal fit. The master die was a prepared left maxillary canine made from heat-polymerized acrylic resin. Daou *et al.* also used the µCT method to study the marginal and internal fit of three-unit FDPs made of pre-sintered Co-Cr and pre-sintered zirconium dioxide (87). The FPDs were made on metal dies of typodont models. The analysis showed similar marginal and internal discrepancy values with the highest values at the occlusal region. When Peroz *et al*. investigated the marginal and internal fit of full ceramic crowns made of lithium disilicate reinforced glass ceramic which were cemented to human premolars they concluded that µCT was an accurate technique for assessing cemented restorations (88). In an attempt to evaluate the triple- and dual-scan method the same test specimens used in the present studies were scanned according to the protocol described by Pimenta *et al.* (25). The µCT method was tested by the author at Bruker µCT´s facility in Belgium. Both the SkyScan 1173, the 1275, and the 2211 were used in the testing. Unfortunately, none of them succeeded in capturing an image of the internal cement space. One possible reason for the lack of results was the physical properties of the materials being tested. In the analyses of the digital files from the three scanners the internal cement space could not be distinguished using the designated software. This was probably because of a too large relative mass difference between the two materials tested; the abutment (KaVo typodont, plastic resin) and the coping (cobalt-chromium) (Personal communication, Bruker µCT´s technician). Only cobalt-chromium was tested as it was considered to be the most challenging material to compare to the plastic resin of the typodont teeth. Daou *et al.* also reported that insufficient radiographic contrast may have limited the accuracy of the analysis when investigating internal fit of FDPs with the µCT method (87).

Borba *et al.* reported that "*the limits between the metal dies and restoration were not clear enough to perform a 3D analysis (i.e. to measure the volumetric dimension of the gap).*" (32).

5. Triple-scan method versus dual-scan method. The triple-scan method described by Holst *et al.* (27) involves an industrial scanner, whereas a table top scanner is used in the dual-scan method described by Lee *et al.* (28). Comparing the two methods shows that the triple-scan method is more comprehensive in respect to resources needed compared to the dual-scan method. The first method tested involves the use of an industrial scanner and an operator. This leads to higher cost per scan compared with the dual-scan method. The second method tested involves use of a table-top scanner already found in many dental laboratories and operated by a dental technician, and therefore these investigations are more affordable. This method is valid as long as the scanner´s resolution is satisfactory, i.e. a resolution comparable to that of an industrial scanner. In Paper I the precision of the industrial scanner was said to be 4 µm and in Paper III the table-top scanner´s precision was stated to be <10 µm. When investigating the internal cement space using the triple-scan method the copings are placed on the abutments without any substitute for the cement. This can result in a tighter fit than what is true in a clinical situation. When using the dual-scan method the cement is replaced by a layer of silicone. It could be argued that this method gives a more realistic and accurate situation.

As the results of the analyses conducted in Papers I and III coincided it can be confirmed that the dual-scan method and the triple-scan method were equally well suited for the investigation of internal fit for fixed dental prostheses. Considering 1) the number of scans needed; two versus three, 2) test equipment needed; table top scanner versus industrial scanner, and 3) the scanning set-up; with and without silicone as cement layer analogue versus abutment, framework placed on abutment, and intaglio of framework; it can be recommended to use the dual-scan method for further analyses.

In many ways, the triple-scan and dual-scan methods have many similarities. Therefore, the discussions regarding triple-scan method versus replica, direct view, and µCT methods are also valid for the dual-scan method.

6. Shortcomings with the dual-scan and triple-scan methods. Apart from being new and relatively untested methods, the triple-scan and dual-scan methods have some limitations. Reflective surfaces may be an issue. For example, the highly reflective surface of milled zirconium dioxide required the intaglios to be sprayed when conducting the triple-scan examination. To avoid bias, all FDP intaglios in Papers I and II were sprayed with titanium dioxide. Also, the cement layer analogue had to be sprayed with Finoscan when conducting the dual-scan examination (Paper III). Spraying with any substance is a possible source of error. However, it has been found that spraying with titanium dioxide prior to scanning did not affect the results (27, 34). As the tables of declaration for Finoscan used in Paper III listed only alcohol and butane, it is reason to assume that it did not interfere with the results as both substances evaporate within a short time after being applied, leaving only the reflective layer (83). In studies on the fit of FDPs using digital means it is important to report the software version. Haddadi *et al.* showed that a software version has an impact on the accuracy of an intraoral scanner (89). In Paper III the single crown FDPs were placed on the abutment with finger pressure which could influence the thickness of the silicone layer. However, this resembles the clinical situation and is also frequently used in experimental studies (90-92).

7. Other methodological limitations. While previous studies have chosen a limited, but evenly distributed, number of measuring points, the possibility to choose a larger number of measuring points is made possible with digital methods of measurement. This was considered to be of great importance and enrichment for the study of internal cement space.

There are three major methodological considerations with methods used for analysis of FPDs´ internal fit. One is the number of measured specimens. Due to costs for production and analysis of each material and each production method, the number of different specimens were three (n=3). This was compensated for by investigating a larger number of points per section. Using the triple-scan method in Paper I, 32 points in the bucco-palatal section and 30 points in the mesio-distal section of the central incisor of each specimen were analysed. Using the triple-scan method in Paper II, analysing the specimens in the bucco-palatal direction, 35 and 33 points were measured for the first molar and first premolar, respectively. In the mesio-distal direction the numbers were 29 and 24 points, respectively. For the investigation of the marginal band width in Papers II and III data from 24 measuring points of each specimen were analysed. In Paper I approximately 197 000 points on a 106 mm^2 large area per specimen were recorded when analysing the maximum cement space and average cement space. In Paper III when analysing the internal fit of a single crown FDP with the dual-scan method, two additional sections were made in the bucco-palatal and mesio-distal directions compared with Papers I and II using the triple-scan method. The result was 279 measuring points in the bucco-palatal direction and 252 measuring points in the mesio-distal direction. This totalled 531 measuring points per test specimen. All in all, this resulted in a considerably larger number of measuring points than what has been used previously. In a review article by Boitelle *et al.* it was shown that the number of measurement points varied between 4 and 385 for conventional methods and more than 3500 for three-dimensional methods (93). In Paper I on internal fit of single crown FDP on a maxillary incisor approximately 106 000 points per abutment tooth were registered. In the studies by Falk *et al.* (84) (Figure 13) and Molin and Karlsson (94) nine and 24 points, respectively, per abutment tooth were recorded. In a study on marginal fit Groten *et al.* found that 50 measurements were required for clinically relevant information about gap size (95). This was regardless of whether the measurement sites were selected in a systematic or random manner. Nawafleh *et al.* pointed out that most authors use only 4 to 12 points (18). Another advantage with both methods used in our studies is that it is possible to subsequently choose additional measuring points and conduct additional analyses.

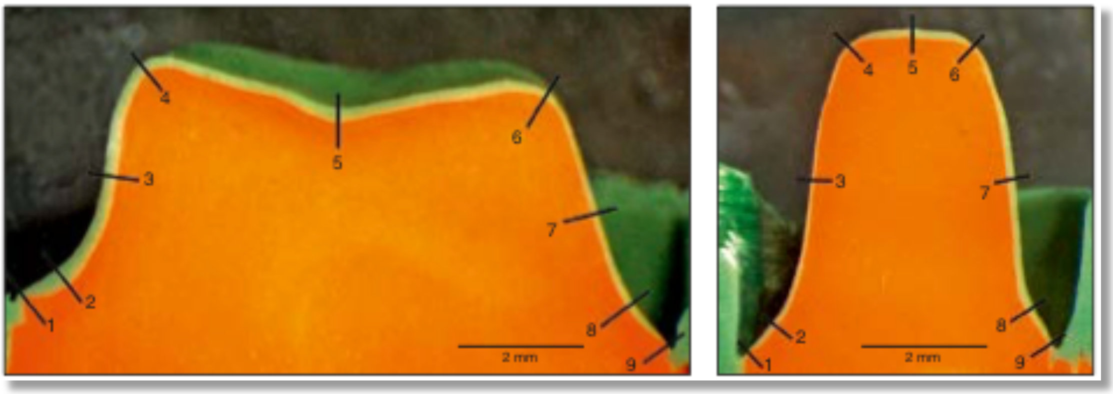

Figure 13. Points measured in the study by Falk et al. (84).
Photo by Håkan Fransson and Anders Falk. With permission

It was also assumed that more points would achieve more accurate estimates of the mean internal cement space. This assumption is now supported as the articles based on the studies have been scrutinized by statisticians at renowned journals and later accepted for publication. In addition, all possible sources of variation associated with the scanning were limited as only one digital scan was taken and used in the design-phase of the production.

The rationale for the presented studies was not to investigate the variation within each material and production technique, but to compare the different materials and production techniques with each other and to a reference method. We assumed that the internal cement spaces for each of the different types of FDPs included in the study were similar. The assumption was made because the same manufacturers´ settings were used to produce the three test specimens of each material. The similarities between specimens for a given material implied that the variation in each measuring point for the three specimens was small, and that the variation obtained was due to differences in cement space along the measuring planes.

The second methodological limitation is related to the geometric tracking system defining the limits of the marginal gap measured when using the triple-scan method as stated by Boitelle *et al.*(93). Svanborg *et al.* discussed that the triple-scan method may not be the most suitable tool for measuring the absolute marginal gap due to problems capturing the outermost margin of the FDP (35). This was pointed out in Paper I and was supported by the statement of Holmes *et al.* that a standardization of misfit measurement was not possible, the reason for leaving out the marginal cement space in Papers II and III (1).

The third methodological limitation is that the methods used were, at the start of our studies, not yet compared against other testing methods. The triple-scan method was first described in 2011 by Holst *et al.* (27). As of November 2019, this study has been cited 24 times in Web of Science Core Collection. The number of studies using the triple-scan method are even more limited and review articles of this method are lacking. Still, in the study by Boitelle *et al.* from 2018 they concluded that the triple-scan method was more reliable than the replica method (85). The study by Lee *et al.* describing the simplified dual-scan method was published in November 2017 and has by November 2019 two citation in Web of Science Core Collection (28). In a recent study by Zimmermann *et al.* a proprietary 3D digital software program was used to measure the fit of ceramic restorations (96). Although Zimmerman didn´t cite Lee *et al.*´s study, and claims to propose a new technique, it is easy to see their similarities.

The question is, how many times does a method have to be repeated to be accepted as approved? It is also impossible to know the true values since all methods give assumptions of the true values. Measurement accuracy can be expressed as the closeness of the evaluation result to the true value. Boitelle *et al.* concluded that all data presented established the reliability of the triple-scan method, due to its low repeatability coefficient, a high intraclass correlation coefficient, and reduced measurement errors compared with the replica method (85). The repeatability coefficient is used in quantifying the reliability of evaluation methods when the trials are repeated several times and is a precision measure. The intraclass correlation coefficient describes how strongly units in the same group resemble each other and the measurement error represents the difference between a measured value and its true value.

The test specimens made by digital techniques were produced from the same STL file where as those FDPs made from the lost-wax and metal casting technique were based on three different silicone impressions and three gypsum models. For the CAD/CAM specimens the variation was limited to the CAM. The old technique may introduce more variability like human errors and changes in properties of the materials as described in the introduction.

Internal fit of different test specimens

The clinical acceptability of marginal gaps was assessed in an *in vitro* study by Bronson *et al.* Pre-doctoral students and prosthodontists first evaluated single crown FDPs with an explorer, then the crowns were examined with the direct view technique. The manual evaluation was repeated 6 months later. Both students and prosthodontists regarded gaps up to 200 µm as clinically acceptable. The width of the gaps ranged from 40 µm to 615 µm (97). Many studies, i.e. the study by Lee *et al.* (98), conclude that the results are clinically acceptable and refers to McLean and von Fraunhofer that states that a marginal fit <120 µm are clinically acceptable (21). In our Papers we refer to the numbers found, not a limit set in 1971. The study by McLean and von Fraunhofer can be disputed as it itself refers to and is based on unpublished data (21).

Even if cement film thickness and internal fit of FDPs are important factors for a restoration´s retention, these factors have not been studied to the same extent as the marginal fit (99). The reason might be that in a clinical situation it is easier to investigate the marginal gap than the internal fit using mechanical methods. After shifting to digital methods as the dual- and triple-scan method it is easier to perform studies on the internal fit. It is also easier to do more comprehensive investigations with unlimited measuring points. The dual-scan method can be used chair-side, i.e. *in vivo*, while the triple-scan method has to be used *in vitro*.

Which is most important out of internal and marginal fit? In a review article by Sailer *et al.* on all-ceramic and metal ceramic tooth-supported FDPs the following were reported as technical complications: framework fracture, ceramic chipping, marginal discoloration, loss of retention, and poor aesthetics. The biological complications were loss of abutment tooth vitality, abutment tooth fracture, and secondary caries (13). The authors concluded that all-ceramic FDPs exhibit similar survival rates as metal-ceramic FDPs after a mean observation period of at least three years.

One can suspect that a too large cement space, aka the internal fit, will influence on the longevity of a ceramic-based FDP as cement has different mechanical properties than the FDP. Loss of retention has been reported to occur at a rate of between 0.6% and 4.7% (13). The reason for this is most likely a cement space that is too large (9). Nevertheless, internal fit is one of several factors influencing the retention of FDPs. For cementing with water-based cements Goodacre *et al.* proposed several factors regarding the preparation for complete crowns to obtain adequate retention: 1) total occlusal convergence (TOC) between 10 and 20 degrees, 2) a minimum of three millimetres occluso-/inciso-cervical dimension of incisors and premolars prepared within the recommended 10 to 20 degrees of TOC, 3) a minimum of four millimetres occluso-/inciso-cervical dimension of incisors and molars prepared within the recommended 10 to 20 degrees of TOC, 4) a ratio of at least 0.4 for the occluso-/inciso-cervical dimension of a prepared tooth in the facio-lingual dimension, and 5) teeth to be prepared with preserved facio-proximal and linguo-proximal corners (100). Bonded FDPs require other considerations. May *et al.* concluded that 1) failure loads decreased with increasing resin cement thickness, 2) well-fitted bonded crowns could withstand more than twice the load before cracking compared to non-bonded crowns, 3) the bonding effect is lost for misfits larger than approximately 450 μm, and 4) polymerization shrinkage can cause tensile stress that can cause fracture with thicker cement even before loading (15).

A search refined on [Dental Oral Surgery Medicine] for [marginal fit] on Web of Science Core Collection reveals 1003 articles of which 38 are review articles. The same type of search for [internal fit] reveals 619 articles of which 25 are review articles. A reason for the higher number of studies on marginal fit compared to internal fit can be due to secondary caries as the largest reason for failure of FDPs according to Sailer *et al.* (13). There is reason to believe that an overextended FDP on an abutment retains bacteria responsible for caries and marginal inflammation. The same applies to an underextended FDP where prepared tooth substance probably retains bacteria in a similar way.

Pre-sintered zirconium dioxide. The results of Papers I and III showed that the internal fit of FDPs made of pre-sintered zirconium dioxide was larger compared to FDPs made of cast cobalt-chromium. Therefore, the results of Papers I and III differ from Lee *et al.* who found that the marginal and internal fit of single crown FDPs made from milled pre-sintered zirconium dioxide and from Ni-Cr by the lost-wax and metal casting technique all exhibited clinically acceptable marginal and internal discrepancies (<120 μm). 11 points were measured in each specimen using the replica method (98). Paper I revealed a quite substantial difference between pre-sintered zirconium dioxide and cast cobalt-chromium.

Sintered zirconium dioxide. Borba *et al.* found in 2011 that single crown FDPs made from sintered zirconium dioxide exhibited inferior fit compared to FDPs made from pre-sintered zirconium dioxide (32). There was no control group in their study, but they referred to a study that stated that three-unit restorations produced with CAD/CAM technology presented similar gap dimensions as restorations made by the lost-wax metal casting technique (101). In Papers I and III we found that single crown FDPs made from the lost-wax and metal casting technique exhibited a tighter fit than sintered zirconium dioxide. A reason for the different results could be the different testing methods, μCT method versus triple-scan method. Büchi *et al.* examined frameworks for 4-unit anterior FDPs made from sintered and pre-sintered zirconium dioxide. They found was that there were no differences between the products. A major shortcoming with the study, which makes it totally unacceptable, was that all frameworks were manually adjusted by an experienced dental technician (102).

Milled lithium disilicate reinforced glass ceramic. The results of Paper I showed that the internal fit of FDPs made of milled lithium disilicate reinforced glass ceramic was larger compared to FDPs made from cast cobalt-chromium. This agrees with Colpani *et al.* who analysed internal and marginal fit of single crown FDPs in milled lithium disilicate and cast cobalt-chromium at five measuring areas with the replica method. They concluded that all evaluated frameworks showed clinically acceptable values for marginal and internal adaptation (103). The results were contrary to Al Hamad *et al.* who found similar fit between milled lithium disilicate single crown FDPs and cast cobalt-chromium FDPs. This study showed that there were no differences between the type of materials and production methods tested regarding the marginal and internal fit. The only deviation found was that the axial fit of

CAD/CAM produced FDPs was smaller than for the conventionally produced FDPs (104). As the study did not reveal the settings used in CAD/CAM production it is impossible to determine if the settings were the reason for the differences in fit or not.

Milled cobalt-chromium. Nesse *et al.* found that three-unit FDPs made from milled cobalt-chromium showed the best results compared to sintered and cast cobalt-chromium (105). This is contrary to Örtorp *et al.* who found that three-unit FDPs made from direct laser metal sintering (DLMS) had the best fit followed by FDPs made from milled wax with lost-wax method, conventional lost-wax method, and milled Co-Cr (73). Paper II showed that there were no significant differences between the tested materials and production methods.

Sintered cobalt-chromium. In Papers I-III, both single crown FDPs and three-unit FDPs made from sintered cobalt-chromium exhibited what McLean and von Fraunhofer considered to be clinically acceptable values of internal fit (21). In Paper I, sintered cobalt-chromium exhibited values of internal fit which were second best to cast cobalt-chromium. In several other studies, restorations produced by sintering technique exhibited better marginal fit compared to restorations produced by lost-wax and metal casting technique (73, 106-109). Nesse *et al.* compared FDPs made from sintered cobalt-chromium to cast and milled cobalt-chromium and found that sintered cobalt-chromium did not reach clinically acceptable values. The conclusion was drawn without stating which values which were regarded as too high (105).

Cast cobalt-chromium. In Paper I the values for the fit of single crown FDPs made by the lost-wax and metal casting technique were found to be lowest. These results are in agreement with Park *et al.* who found that single crown FDPs made by the lost-wax and metal casting technique had the tightest fit compared to FDPs made by milled and sintered cobalt-chromium (110). Seven points were measured in bucco-palatal and mesio-distal direction , respectively, using the replica method. Our results are contrary to those of Al Hamad *et al.* who in their study of single crown FDPs made from zirconium dioxide, lithium disilicate, and cobalt chromium using three different production techniques found that 1) the type of crown had no effect on the marginal and internal fit of single crown FDPs, 2) the manufacturing had no effect on the marginal and occlusal fit, and 3) the CAD/CAM production method produced the smallest axial fit compared to the conventionally produced FDPs (104).

General aspects. The various test specimens have miscellaneous challenges in the production methods. It might be more difficult to achieve the desired, or preset, fit of FDPs made from pre-sintered zirconium dioxide compared to sintered zirconium dioxide. One reason is that the pre-sintered framework is milled in green state (un-sintered, soft) which shrinks about 20-25% during the final sintering process. The settings for the sintering process are individually set by the manufacturer for each batch of zirconium dioxide blanks. A multi-unit FDP made by the lost-wax and metal casting technique may have difficulties in fulfilling the desired qualities due to challenges with the alloys to reach the most distant nooks and crannies during the casting process. It is also reason to believe that milled FDPs achieve a larger fit in the innermost corners compared to sintered FDPs due to drill compensation. In spite of these differences the present thesis showed that the fit of different FDPs were similar and clinically acceptable. The results showed that the null-hypothesis could not be rejected.

9. Conclusions

- Single crown FDPs made by the lost-wax and metal casting technique had a tighter fit than crowns made by milled cobalt-chromium, zirconium dioxide, and lithium disilicate, and laser sintered cobalt-chromium.

- Three-unit FDPs made by the lost-wax and metal casting technique had a comparable fit to that of three-unit FDPs made by milled cobalt-chromium, zirconium dioxide, and lithium disilicate, and laser sintered cobalt-chromium.

- Both dual-scan method and triple-scan method are reliable methods for the investigation of internal cement space of single crown fixed dental prostheses.

10. Clinical implications

The results of our studies showed that no production methods using different materials were able to produce FDPs with cement spaces according to the manufacturers´ settings (Papers I-III). The evaluation of fit in the present studies was related to the use of water-based cements where the clinically acceptable value was 120 µm (21). It has been recommended that an internal fit of 50–100 µm is used for resin-based cements (15). The findings in this thesis indicates that the internal fit exceeded these values for all types of materials and production methods. In cases where a tight fit is wanted, as with the use of resin-based cements, it is advisable to adjust the settings in cooperation with the dental technician.

The fit amongst the tested specimens were similar and therefore other factors than the width of the cement space are necessary to consider when deciding the type of FDP for a specific reconstruction. Aesthetics, function, and strength must also be taken into consideration. For multi-unit FDPs the connector area is crucial. Restorations made from Co-Cr requires a minimum connector area of 6.25 mm^2 (2.5 x 2.5 mm) (111). For FDPs made from zirconium dioxide a recommended connector is 7.0-9.0 mm^2 (112, 113).

The use of dual-scan method can easily be implemented in a digitalised clinic when evaluating the fit of fixed dental prostheses. With a simplified version of the replica method where a layer of silicone resembles the cement it is only possible to visually inspect and study the thickness of the cement layer. With the dual-scan method it is possible to quantify this layer. This is as mentioned earlier more important for adhesively than conventionally cemented restorations.

11. Future perspectives

As for all studies, both those in new fields, and those on the fringe between old and new knowledge, it is important to get the results confirmed. Neither the triple-scan nor the dual-scan method are widely used when evaluating the internal fit of FDPs. It is therefore important to perform further studies to validate these methods. Especially the dual-scan method as it is less complicated, less time consuming, and more clinically applicable.

With the knowledge obtained from my studies I can now perform additional investigations on the fit of fixed dental prostheses. For example, clinical studies on both single crown FDPs and multi-FDPs using the dual-scan method, studies on the effect of veneering, and additional studies with equivalent setup but with a larger number of test specimens. An interesting aspect would be to make a closer examination of the setting parameters in relation to marginal and internal fit.

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13. Errata

Paper I: DAHL, B.E., RONOLD, H.J. & DAHL, J.E. Internal fit of single crowns produced by CAD-CAM and lost-wax metal casting technique assessed by the triple-scan protocol. 2017. *J Prosthet Dent*, 117, 3. 400-404.

Correct figure legends are as follows:

Figure 1. Specimen of mesio-distal section from GOM Inspect. Mesio-distal section was divided into 5 subsections: mesial, mesio-occlusal, occlusal, disto-occlusal, and distal with 9, 3, 4, 3, and 9 measuring points

Figure 2. Specimen of bucco-palatal section from GOM Inspect. Bucco-palatal section was divided into 4 subsections; buccal, incisal, palatal, and palato-gingival with 11, 6, 7, and 6 measuring points

14. Papers I-III

I

THE JOURNAL OF PROSTHETIC DENTISTRY

RESEARCH AND EDUCATION

Internal fit of single crowns produced by CAD-CAM and lost-wax metal casting technique assessed by the triple-scan protocol

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ABSTRACT

Statement of problem. Whether single crowns produced by computer-aided design and computer-aided manufacturing (CAD-CAM) have an internal fit comparable to crowns made by lost-wax metal casting technique is unknown.

Purpose. The purpose of this in vitro study was to compare the internal fit of single crowns produced with the lost-wax and metal casting technique with that of single crowns produced with the CAD-CAM technique.

Material and methods. The internal fit of 5 groups of single crowns produced with the CAD-CAM technique was compared with that of single crowns produced in cobalt-chromium with the conventional lost-wax and metal casting technique. Comparison was performed using the triple-scan protocol; scans of the master model, the crown on the master model, and the intaglio of the crown were superimposed and analyzed with computer software. The 5 groups were milled presintered zirconia, milled hot isostatic pressed zirconia, milled lithium disilicate, milled cobalt-chromium, and laser-sintered cobalt-chromium.

Results. The cement space in both the mesiodistal and buccopalatal directions was statistically smaller ($P<.05$) for crowns made by the conventional lost-wax and metal casting technique compared with that of crowns produced by the CAD-CAM technique.

Conclusions. Single crowns made using the conventional lost-wax and metal casting technique have better internal fit than crowns produced using the CAD-CAM technique. (J Prosthet Dent 2016;■:■-■)

Single-crown (SC) and fixed dental prostheses (FDPs) are cemented with water-based cement or the adhesive technique. With water-based cement, retention relies on the preparation design and the adaptation of the restoration.[1] A well-adapted restoration is the best possible prerequisite for the success of an FDP.[2] The cement's main task is to fill the space between the abutment and the restoration and thereby prevent the restoration from dislodging and loosening.[3,4] An in vitro study indicated that thinner and more even cement space could improve the strength of the restoration.[5] Despite these important aspects, the cement and internal fit still are the weakest links compared with the tooth substance and restoration.

A variety of methods and testing parameters have been used to evaluate the adaptation of prosthetic restorations, including the mainly direct measurement, cross-sectional measurement, and impression replica technique.[6] The most widely used method of evaluating the adaptation of prosthetic restorations is the replica technique because of its ability to estimate internal and marginal discrepancies.[7,8] With this technique, the cement is replaced with an impression material, and the restoration is placed on the abutment. The restoration and impression material are separated from the abutment, and the thickness of the cement layer analog is measured. Other methods use laser videography,[9] profile projection,[10] microcomputed tomography,[11,12] stereo microscopy,[13] and computer-aided design and computer-aided manufacturing (CAD-CAM) scanning.[14] Most of the newer studies are limited to comparing

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Clinical Implications

Single crowns made from conventional impression and the lost-wax and metal casting technique have a smaller cement space than that of single crowns made from digital intraoral impressions and produced by CAD-CAM.

CAD-CAM systems, and few studies have a control group using a conventional wax pattern and the metal casting technique. A recent review article assessing different methods of determining the fit accuracy of prosthetic restorations provided no conclusive evidence for the best methodology.[6]

The use of digital scanners for shape images allows for a more accurate and comprehensive evaluation of the fitting accuracy of FDPs. Comparing the digital impression of the abutment with the digital scan of the intaglio of the FDP with specifically designed computer software (GOM Inspect software) gives an overall view of the space between the FDP and the abutment. In this study, the triple-scan method described by Holst et al[14] was used to compare the internal adaptation of the frameworks for SCs produced by 5 different CAD-CAM systems to SCs produced by the conventional lost-wax and metal casting technique.

The purpose of this in vitro study was to investigate the cement space of different single crowns produced by alternative methods. The null hypothesis was that the cement space of single crowns produced by CAD-CAM would be similar to that of crowns produced by the lost-wax and metal casting technique.

MATERIAL AND METHODS

A model of the maxilla with teeth from the right third molar to the left third molar was made with KaVo typodont teeth embedded in Type IV gypsum. The left central incisor was prepared with a diamond rotary cutting instrument (ISO 290 014; Horico) for a single crown. A digital impression was made of the typodont model with the intraoral scanner (Trios, serial number t1402c12012b, software build: 1.3.3.1 CL206342; 3Shape). The stereolithography file was sent to a dental technician for CAD-CAM. From the single stereolithography file, 5 different designs were made to fulfill the manufacturer's recommendations for producing the frameworks for the following types of crowns (Table 1): presintered zirconia (Zir; Dental Direkt), hot isostatic pressed yttria-tetragonal Zir polycrystal ceramic (HIP-Zir; Denzir), lithium disilicate reinforced glass ceramic (LiSi; Ivoclar Vivadent AG), milled cobalt-chromium (M-Co-Cr; Eisenbacher Dentalwaren), and laser-sintered cobalt-chromium (LS-Co-Cr; Dentware). Three crowns of each type were produced. Three impressions in polyvinyl siloxane (Imprint 4; 3M ESPE) were taken and 3 frameworks for single crowns were produced with the lost-wax and metal casting technique with cobalt-chromium (C-Co-Cr; Bego) and used as a control. The fabrication was partially provided by centralized production centers. The crowns were not veneered with porcelain. The definitive cast was spaced (Kerr Classic Cement Spacer; Kerr Corp) according to standard laboratory procedure. A total of 18 frameworks were produced. It was specified that the intaglio of the frameworks were to be treated as if they were products ready to be cemented by the dentist.

The master model and the frameworks were scanned (ATOS III Triple-scan; GOM mbH) using the triple-scan method described by Holst et al.[14] The accuracy of the scanner was measured by the manufacturer (GOM mbH) to be 4 μm. Scanning was performed in 3 steps, scanning of the master model, scanning of the framework on the master model, and scanning of the intaglio of the framework. To obtain a scan of the intaglio, the framework had to be sprayed with titanium dioxide (Graphiti GmbH, Brennspiritus; Kluthe GmbH). The second and third scans were used to position the intaglio of the framework on the master model. The distance between the intaglio and the master model was calculated with ATOS Professional software (V8 Hotfix 11, Rev. 89084, Build 2015-10-07; GOM mbH), and the results were analyzed with GOM Inspect software (V8 Hotfix 9, Rev. 84863, Build 2015-04-22; GOM mbH).

The space between the abutment and the restoration is termed marginal discrepancy and cement space. In this study, marginal discrepancy was considered as the distance from the preparation margin and 0.5 mm in the occlusal direction, while the cement space was measured on the distance occlusal to the marginal discrepancy (Fig. 1). One point on each of the mesial, distal, buccal, and palatogingival surfaces was chosen in the GOM Inspect software for the construction of fitting planes. A section was defined as the symmetrical plane between the fitting planes on the buccal and palatogingival and the mesial and distal planes. The thickness of the cement space was recorded in the buccopalatal section at 32 points and in the mesiodistal section at 30 points. The nearest point to the preparation margin was set at 0.5 mm. The buccopalatal section was divided into 4 subsections: buccal, incisal, palatal, and palatogingival with 11, 6, 7, and 6 measuring points (Fig. 1). The mesiodistal section was divided into 5 subsections: mesial, mesio-occlusal, occlusal, disto-occlusal, and distal with 9, 3, 4, 3, and 9 measuring points, respectively (Fig. 2). The average area of the abutments scanned was 106 mm^2, and the average total number of points measured was approximately 197 000 (Fig. 3). Cutoff distance was set to 1.0 mm, implying that measurements exceeding 1.0 mm were considered outliers.

Table 1. Listing of materials and settings used in production of frameworks*

Group	Material	Product	Manufacturer	Production Laboratory	Marginal Cement Space (μm)	Internal Cement Space (μm)
Zir	Presintered zirconium-dioxide	DD Bio ZW iso Zirkonoxid, 3Y-TZP	Dental Direkt	Tannlab	30	70
HIP-Zir	HIP (hot isostatic pressed) zirconium-dioxide	Denzir	Denzir	Denzir	15	50
LiSi	Lithium disilicate	e.max CAD	Ivoclar Vivadent	Scanbiz	20	80
M-Co-Cr	Milled Co-Cr	ED Kera-Disc CoCr	Eisenbacher Dentalwaren	DenTech/Østvold Dental	50	90
LS-Co-Cr	Laser sintered Co-Cr	Dentware CoCr	Dentware	Dentware	55	80
C-Co-Cr	Cast Co-Cr	Wirobond 280	Bego	Tannlab	0*	20*

*According to manufacturer, thickness of one coat of Kerr Classic Cement Spacer is 20 μm. Spacing started 0.5 mm from preparation margin.

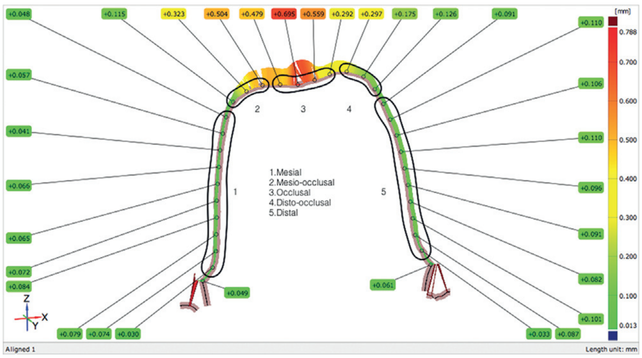

Figure 1. Specimen of buccopalatal section from GOM Inspect. Buccopalatal section was divided into 4 subsections; buccal, incisal, palatal, and palatogingival with 11, 6, 7, and 6 measuring points.

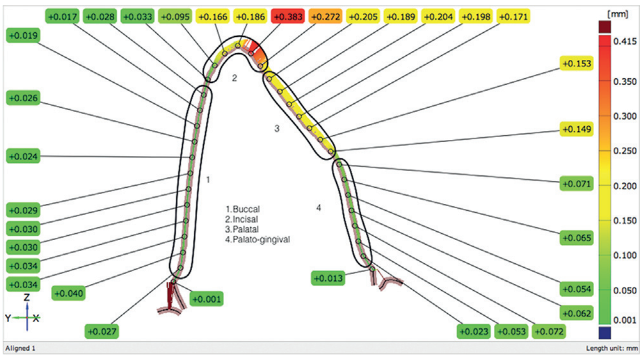

Figure 2. Specimen of mesiodistal section from GOM Inspect. Mesiodistal section was divided into 5 subsections: mesial, mesio-occlusal, occlusal, disto-occlusal, and distal with 9, 3, 4, 3, and 9 measuring points.

The statistical analysis was performed using a spreadsheet (Excel 2011 for Mac v14.6.2; Microsoft Corp) using the Student *t* test to compare each material with cast Co-Cr for each subsection (α=.05).

RESULTS

The results are shown in Tables 2 to 5. The measurements in the buccopalatal direction showed that the cement space was wider in the incisal and palatal

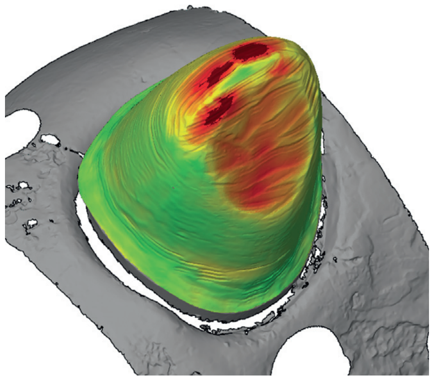

Figure 3. Illustration of abutment with specimen of cement space measured using GOM Inspect. Colored area represents scanned area of abutments (approximately 106 mm^2 and approximately 197 000 measured points).

sections than in the buccal and palatogingival sections (Table 2). In the mesial-distal direction, the cement space was wider at the incisal section than at the mesio-occlusal, disto-occlusal, mesial, and distal sections (Table 3). Comparing the CAD-CAM groups with the C-Co-Cr groups, all measurements except for the palatogingival sections and the buccal sections for the HIP-Zir and M-Co-Cr groups were statistically significantly greater (P<.05). All internal sampling points for the buccopalatal and mesial-distal sections are summarized in Table 4, which shows that all restorations made with the CAD-CAM technique had a larger cement space than the restorations in the control group made with the lost-wax and metal casting technique. The differences were statistically significant. An analysis of approximately 106 mm^2 and 197 000 points per abutment/crown in the GOM Inspect software (without the possibility of statistical calculation) revealed the average maximum space and the average space of the 3 specimens in each material group (Table 5). The highest average maximum space of 776 μm was found in the Zir-group, and the smallest average maximum space in the control group C-Co-Cr-group with 193 μm.

Table 2. Cement space (μm) in different subsections of buccopalatal direction (mean ±SD)

Subsection	Zir	HIP-Zir	LiSi	M-Co-Cr	LS-Co-Cr	C-Co-Cr
Buccal	36 ±9	66 ±20*	94 ±32	45 ±7*	88 ±18	63 ±33
Incisal	202 ±113	140 ±70	125 ±56	234 ±124	155 ±50	72 ±27
Palatal	171 ±25	203 ±27	102 ±33	231 ±39	97 ±11	65 ±13
Palatogingival	57 ±14*	69 ±19*	68 ±25*	64 ±18*	57 ±10*	65 ±17

*All CAD-CAM specimens had statistically significant larger cement spaces compared with C-Co-Cr group except palatogingival subsection and two groups of buccal section.

Table 3. Cement space (μm) in different subsections of mesiodistal direction (mean ±SD)

Subsection	Zir	HIP-Zir	LiSi	M-Co-Cr	LS-Co-Cr	C-Co-Cr
Mesial	70 ±12	52 ±11	65 ±24	68 ±27	104 ±15	41 ±14
Mesio-occlusal	259 ±157	188 ±109	149 ±74	297 ±127	148 ±29	82 ±26
Occlusal	485 ±141	355 ±60	262 ±133	595 ±96	221 ±35	102 ±36
Disto-occlusal	183 ±88	199 ±88	227 ±95	277 ±122	166 ±50	100 ±34
Distal	82 ±17	90 ±19	92 ±19	76 ±34	47 ±13	42 ±19

All CAD-CAM specimens had statistically significant larger cement spaces compared with C-Co-Cr group.

Table 4. Evaluation of entire internal fit section (margins excluded) for all internal sampling points in buccopalatal and mesiodistal sections

Specimen	Buccopalatal, Mean ±SD (μm)	Mesiodistal, Mean ±SD (μm)
Zir	105 ±89	165 ±164
HIP-Zir	113 ±68	138 ±115
LiSi	97 ±41	128 ±97
M-Co-Cr	130 ±107	193 ±199
LS-Co-Cr	97 ±41	114 ±65
C-Co-Cr	66 ±25	61 ±35

A total of 522 points per group in buccopalatal and mesiodistal section were analyzed. All specimens had statistically significant larger cement spaces than C-Co-Cr.

Table 5. Marginal discrepancy and cement space (μm) based on measurements on entire prepared abutment and intaglio of crown (mean ±SD)

	Marginal Discrepancy and Cement Space*	
Specimen	Maximum	Average
Zir	776	78 ±65
HIP-Zir	325	81 ±56
LiSi	521	76 ±47
M-Co-Cr	465	90 ±78
LS-Co-Cr	286	82 ±37
C-Co-Cr	193	58 ±23

Data from GOM Inspect: 106 mm^2 and 197 000 points per abutment/crown. *Average of 3 specimens in each group.

DISCUSSION

A widely used method of studying the cement space and marginal discrepancy is the replica method.[6] This method involves surveying the thickness of a silicone layer by using a microscope. The mixing, dispensing, and handling of the silicone for the cement replica are possible sources of error. By using the triple-scan method described by Holst et al,[14] one can eliminate the manual sources of error. The objects can be digitally compared by scanning the master model, the intaglio of the restoration, and the restoration in place on the master model, followed by superimposing the digital files.

As unlimited ways exist of sectioning the digital model and restoration, the points one can survey are also unlimited. Previous studies using the replica method have sectioned the model mesiodistally and buccolingually.[6] The present evaluation was also performed on 2 sections: mesiodistally and buccopalatally. One section was determined as the mean between the fitting plane on the mesial and distal surfaces and the other section as the mean between the fitting plane on the buccal and palatogingival surfaces. The mesial-distal section was therefore on the palatal surface, not on the incisal edge. As an alternative to study sections, the total volume of the cement space was considered. Based on the difficulties in determining the preparation margins at the level of accuracy used and the observation that all crowns appeared more or less short of the preparation margin, a volumetric analysis was considered inappropriate.

The intaglios of the FDPs were highly reflective, and one possible source of error with the triple-scan method was the need to spray them with titanium dioxide powder to reduce the reflectiveness. The results of the scanning may have shown a tighter fit and thinner cement space because of the thickness of the titanium dioxide. In the studies by Holst et al[14] and Matta et al,[15] this source of error was considered insignificant.

The veneering of porcelain may affect marginal and internal fit. However, in a review article by Contrepois et al,[16] this aspect seems not to be clarified. Eight studies concluded that the effects of porcelain veneering on marginal fit were not significant, and 5 studies found that porcelain veneering substantially widened marginal discrepancy.[16]

Three different production techniques were compared in this study: traditional lost-wax and metal casting, milled, and laser sintered. The smallest cement space based on all measured areas was obtained with wax pattern and metal casting, followed by laser sintered, and milled. Anadioti et al[17] found that pressed ceramic crowns made from a conventional impression exhibited a better internal fit than those made from a digital impression. In a recently published review and meta-analysis of digital and conventional impressions, no differences were found between the procedures.[18] Dental restorations fabricated with the digital impression technique presented statistically similar internal fit compared with those obtained with the conventional impression technique.

The milling of geometric shapes like the intaglio of a dental crown was difficult to obtain with the desired precision. This was especially so for the cobalt-chromium-based alloy in this study. The test specimens of the different milled groups were made at different production facilities and with different milling machines. The differences observed in the milled groups could therefore have been caused by different material properties, by the manufacturing process, especially the CAM procedure, or by a combination of the two.

Our results from the CAD-CAM specimens also showed that the cement space in some areas deviated substantially from the manufacturer's settings (Table 1). This was most apparent in the palatal sections and difficult to explain. In addition, it is reasonable to believe that the cement space in the innermost corners was even larger because of the size and shape of the milling burs, although that was not measured.

Similar studies with a larger number of single crowns are needed to confirm or refute the hypothesis that single crown made with the CAD-CAM technique have an internal fit comparable to crowns made with the conventional impression and lost-wax and metal casting technique. Further studies are also needed to establish the triple-scan method as the preferred method of investigating the internal fit of FDPs.

CONCLUSIONS

Because of the limited number of crowns tested, no conclusions can be drawn as to whether one production method is better than another. However, the newer CAD-CAM techniques did not exceed the conventional procedure with lost-wax and metal casting in the hands of an experienced dental technician. Within the limitations of this study, we must reject our hypothesis that the cement space of single crowns produced with CAD-CAM is similar to that of crowns produced with the conventional lost-wax and metal casting technique.

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