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# Production tolerance of conventional and digital workflow in the manufacturing of glass ceramic crowns

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## ABSTRACT

**Objectives.** To measure and compare the size of the cement gap of wax and polymer copings and final glass-ceramic crowns, produced from conventional and digital workflows, one additive and one subtractive.

**Methods.** Thirty wax copings were made by conventional manual layering technique and modeling wax on stone models with spacer varnish simulating a cement spacer. The wax copings were embedded and press-cast in lithium disilicate glass ceramic. Thirty wax copings were produced by milling from a wax blank, i.e. subtractive manufacturing, and thirty polymer burn-out copings were produced by stereolithography, i.e. additive manufacturing. These copings were embedded and press-cast in lithium disilicate glass ceramic in the same manner as the conventional group. The fit of the wax/polymer copings and subsequent crowns was checked using an impression replica method. Mean values for cement gap for marginal, axial, and occlusal areas were calculated and differences were analyzed using Student's t-test.

**Results.** There were significant differences in mean values for accuracy/production tolerance among different manufacturing techniques for both production stages: wax and polymer copings and final pressed glass-ceramic crowns. In general, crowns produced from a digital additive workflow showed smaller mean cement gaps than crowns produced from a conventional workflow or a digital subtractive workflow. Additive polymer copings showed significantly smaller cement gaps than milled wax copings ( $p \leq .001$ ) and conventional wax copings ( $p \leq .001$ ) in the axial area. In the occlusal area, both additive polymer copings and conventional wax copings showed significantly smaller cement gaps than milled wax copings ( $p = .002$  and  $p \leq .001$  respectively). Crowns produced from conventional manual build-up wax copings showed significantly larger mean cement gaps than crowns produced from milled wax and additively manufactured polymer copings in the marginal and axial areas ( $p \leq .001$ ). Among the crowns with smaller cement gaps, crowns produced from additively manufactured polymer copings showed significantly smaller mean cement gaps than crowns produced from milled wax in the marginal and axial areas ( $p \leq .001$ ). In the occlusal

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areas, the differences in mean cement gaps were only statistically significant between crowns produced from conventional manual build-up wax copings and crowns produced from milled wax where the latter ones showed smaller mean cement gaps ( $p = .025$ ).

*Significance.* The present study suggests that an additive manufacturing technique produces smaller mean cement gaps in glass-ceramic crowns than a conventional or subtractive manufacturing technique.

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## 1. Introduction

Caries and loss of retention are two common reasons for failure of single crowns [1]. These types of failure may be influenced by the internal and marginal fit of a restoration. Deficient fit may be a risk factor for loss of retention, for caries at crown margins and/or for influence on gingival conditions and risk of periodontal disease [2,3].

Since the introduction and early attempts of digital workflows in dentistry in the seventies [4], computer-aided design and manufacturing (CAD/CAM) procedures have become common in the manufacturing of dental prostheses. These production techniques are more standardized, less labor intensive, time-saving and therefore cost effective compared to traditional methods [5,6]. Several different computer-aided manufacturing techniques are available. Some suggest differences in production tolerance, and subsequent fit of a restoration, between different production techniques, e.g. decreased precision for manual techniques compared to computerized ones, and differences among CAD/CAM techniques [7,8]. A conventional manual workflow includes a variety of different steps where each step is susceptible to error. Inaccuracies in each step of the workflow may accumulate during the subsequent steps of prosthesis fabrication, lead to compounding errors, and affect the quality of the final restoration. With a digital workflow the number of manufacturing steps may be significantly reduced [5].

Much focus has recently been directed toward analyzing the first step of a digital workflow – impression – and comparison of conventional impression to digital intraoral scanning [9]. Less information is available from comparisons of other steps in conventional and digital workflows. The production of wax- or polymer copings for pressed restorations is a critical step. The quality of a wax coping that is produced by manual build-up is entirely dependent on the skill of the operator. The application of the die hardener and spacer is impossible to fully standardize in manual techniques and these steps may affect the size of the cement gap and marginal and internal fit of the final restoration.

Instead, wax and/or polymer copings may be produced through a digital workflow which is less operator dependent and where the cement space gap is standardized and controlled. A subtractive technique may be used where the coping is milled from a blank, or an additive technique where thin layers of monomer particles are fused together to a polymer coping using stereolithography. Some authors suggest differences among CAM techniques, e.g. limitations in subtractive techniques where the number of axis performing the milling

and the size of the milling burs, control precision and fit, whereas additive manufacturing allow for complex restorations without limitations [7,8].

The general statement that digital workflows are superior to conventional workflows per se may be an erroneous simplification. The digital workflow also consists of a series of steps: data exchange, conversion and processing [10]. Knowledge of random and systematic errors in accuracy in CAD/CAM systems is essential [11]. To our knowledge, there is little information available from comparisons of conventional and digital workflows regarding possible differences in cement gap and fit.

The aim of the present study was to measure the size of the cement gap of wax and polymer copings made from conventional and digital workflows, one additive and one subtractive, as well as measure the size of the cement gap of the final crowns produced and compare the groups. The null hypothesis was that there would be no differences between groups.

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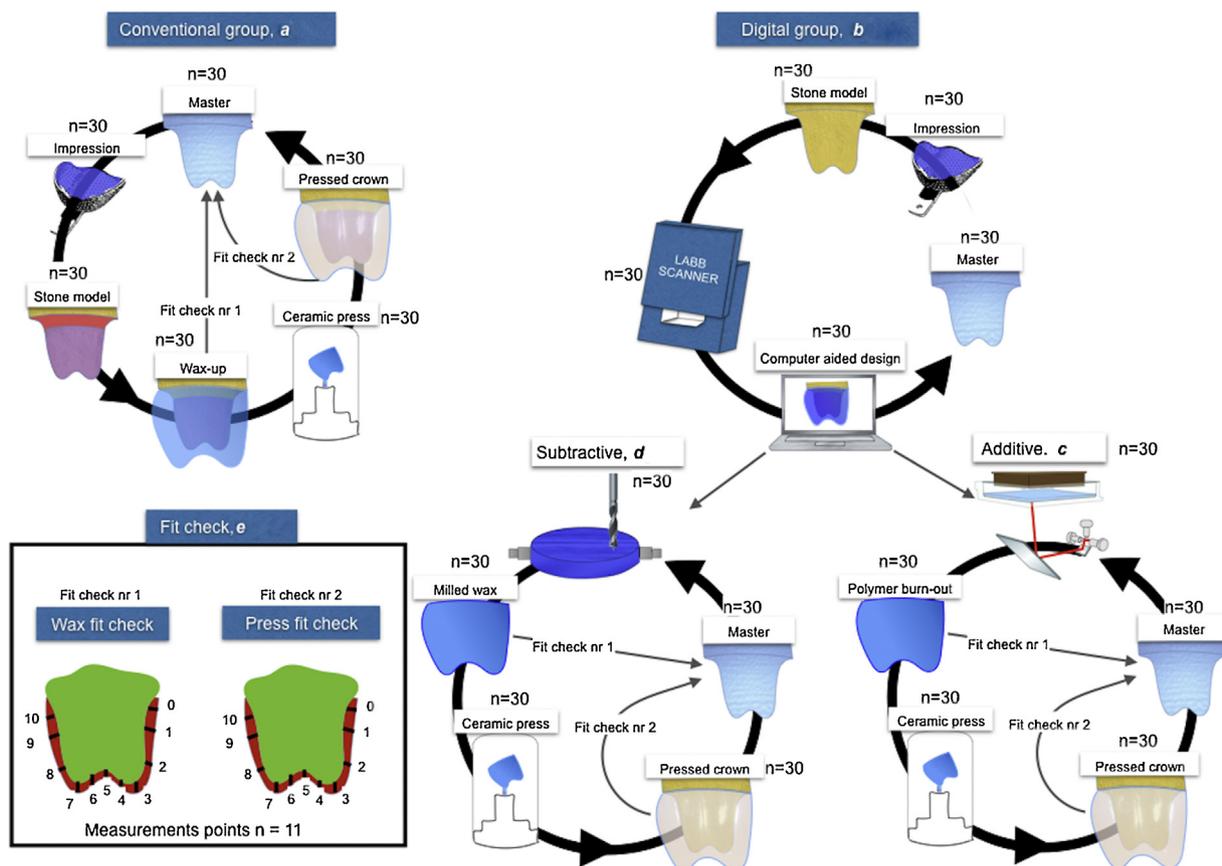
## 2. Materials and methods

The conventional and digital workflows are illustrated in an infographic (Fig. 1a–e).

### 2.1. Reference and master models

An impression of a patient's maxilla was made using an addition silicone impression material (Express 2, 3M ESPE, St. Paul, MN, USA). The impression was cast using an epoxy material (EpoFix Resin Struers, Ballerup, Denmark). Tooth 24 on the cast was prepared for a monolithic glass-ceramic crown with preparation depths and angle of convergence according to the manufacturers recommendations (Ivoclar Vivadent, Schaan, Liechtenstein) using a chamfer-shaped diamond bur, thus creating a reference model.

This reference model was then reproduced sixty times using a silicone impression material (Siliflex, DeguDent, Hanau, Germany) and the impressions were cast using the epoxy material (EpoFix Resin Struers, Ballerup, Denmark), creating sixty master models to be used for cement gap measurements of wax copings and glass-ceramic crowns. These epoxy master models were replicated using silicone impression material (Express 2, 3M ESPE, St. Paul, MN, USA) and cast in dental stone (esthetic-base gold, Dentona, Dortmund, Germany), creating 60 stone models to be used for the manufacturing of wax copings and glass-ceramic crowns (Fig. 2).



**Fig. 1 – (a) Conventional group, manufactured crowns in a conventional way with manual build-up of 30 wax copings and further pressed crowns. (b) Digital group, from stone models to digital model using a laboratory scanner. (c) Additive manufactured group, additive manufacturing of 30 polymer burn-out copings and further pressed crowns. (d) Subtractive manufactured group, subtractive manufacturing of 30 burn-out wax copings further pressed crowns. (e) Fit check, fit of the wax/polymer copings and press crown using an impression replica method, measurements points  $n = 11$ .**

## 2.2. Production of crowns — conventional group

Thirty of the stone models were used to produce crowns in a conventional way with manual build-up of wax copings (Fig. 1a). The models were sectioned and pinned. The die was treated with a stone hardener (die:master duo, Renfert, Hilzingen, Germany), and two  $20\ \mu\text{m}$  layers of die spacer varnish (die:master blue  $20\ \mu\text{m}$ , Renfert, Germany) simulating a cement spacer and finally a thin layer of separator (DVA Very Special Separator, Dental Ventures of America, Corona, CA, USA). The die was then submerged in a first layer of dipping wax (Star Wax D, Dentaurnum, Ispringen, Germany) and then waxed with modeling wax (Wax Giant Blue, YETI Dentalprodukte, Engen, Germany) using conventional manual layering technique until a full anatomy crown was achieved. Each crown was designed individually and numbered together with its corresponding epoxy model.

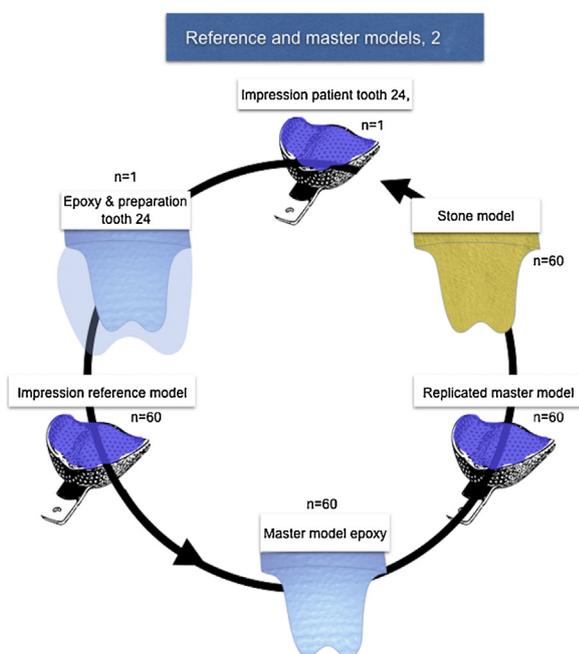
A sprue was waxed onto the palatal cusp of all wax objects, which were then embedded in a universal investment material (IPS PressVest Premium investment, Ivoclar Vivadent, Schaan, Lichtenstein), with 5 crowns in each 200 g ring base. The wax was removed in a heated furnace (EWL 5635, KaVo, Biberach/Riß, Germany) and the crowns were pressed with

lithium disilicate glass ceramic (IPS e-max Press LT A2, Ivoclar Vivadent, Schaan, Lichtenstein) in the machine-calibrated furnace (Programat EP 5010, Ivoclar Vivadent, Schaan, Lichtenstein.) All the steps in the workflow were performed according to the manufacturers' recommendations.

## 2.3. Production of crowns — CAD/CAM groups

Thirty of the stone models were used to produce crowns with CAD/CAM-technique from wax or polymer copings. The models were sectioned and pinned. The models were then scanned using a laboratory scanner and software (3Shape D900L, Dental designer 2016, Copenhagen Denmark, software version  $\times 64$  build 16.4.0). Each crown was designed individually and numbered. Default data for cement gap ( $40\ \mu\text{m}$  marginal cement gap,  $80\ \mu\text{m}$  internal cement gap) and drill compensation ( $0,7\ \text{mm}$  drill radius,  $0,71\ \text{mm}$  drill compensation offset) were used. Thirty standard tessellation language (STL) files were created and used to produce 30 crowns by additive manufacturing and 30 crowns by subtractive manufacturing (Fig. 1b).

The designs were imported into a stereolithography machine (Formlabs Form2, Formlabs, Somerville, MA, USA) using the recommended software (Preform 2.10.1, Formlabs,



**Fig. 2 – Reference and master models, production of a 60 master model epoxy and 60 stone model.**

Somerville, MA, USA) for additive manufacturing of polymer burn-out copings (Fig. 1c). The support structures were connected to the occlusal surfaces. The print was conducted with a 25  $\mu\text{m}$  layer thickness using a polymer material (Castable V2, Formlabs, Somerville, MA, USA). Postprocessing consisted of cleaning for 90 s each in two ultrasonic baths containing isopropyl alcohol (Unimedica, Matfors, Sweden). The copings were then dried with compressed air and placed in a UV-light chamber (LC 3DPrint Box, NextDent, Soesterberg, Netherlands) for 15 min post curing. After curing, all support structures were removed.

The designs were also imported into CAM-software (hyperDENT V7.6, FOLLW-ME Technology Group, München, Germany) for subtractive manufacturing of 30 wax copings in a milling machine (Datron D5, Datron, Darmstadt, Germany) from a wax blank (CAD/CAM wax blanks, YETI Dentalprodukte, Engen, Germany) (Fig. 1d).

A sprue was waxed onto the palatal cusp of all objects, which were then invested, divested and cast in lithium disilicate glass-ceramic in the same manner as described above.

#### 2.4. Fit check

Prior to pressing, the fit of the wax/polymer copings was checked using an impression replica method. Each wax/polymer coping was filled with a light body silicone material (Aquasil Ultra XLV, Dentsply International, York, PA, USA) and placed onto its corresponding epoxy model using a 500 g vertical load. When the light body layer had set, the coping was removed from the model and filled with a heavybody silicone material (Aquasil Ultra Heavy, Dentsply International, York, PA, USA) to stabilize the thin layer of light body silicone material. The resultant silicone replicas were sectioned into two pieces by using a fine blade (Carbon Steel Blade #11, BRAUN,

Aesculap AG). Measurements were performed at eleven points using a light microscope (Dino-Lite Digital microscope, AnMo Electronics Corporation, Taiwan) and software (Dinocapture 2.0, version 1.5.19, AnMo Electronics Corporation, Taiwan) (Fig. 1e). Measurements from points 0 and 10 were analyzed as one group representing the marginal area of copings and crowns. Measurements from points 1, 2, 8 and 9 were analyzed as one group representing the axial area of copings and crowns. Measurements from points 3, 4, 5, 6 and 7 were analyzed as one group representing the occlusal area of copings and crowns.

The microscope was digitally calibrated according to the manufacturer's instructions. The same process was used to check the fit of the final glass-ceramic crowns on their corresponding epoxy master models. All measurements were performed by one operator.

#### 2.5. Statistical analysis

The data was analyzed using SPSS software (IBM Analytics, V 9.6.0.0, IBM, Armonk, NY, USA). Mean values for cement gap for marginal, axial, and occlusal areas were calculated. Differences in production tolerance between traditional, additive and subtractive production methods were analyzed using Student's t-test. Level of significance was set at  $p < .05$  at 95% confidence interval.

### 3. Results

The present study found significant differences in accuracy/production tolerance between traditional and digital workflow manufacturing. The null hypothesis is thus rejected.

There were numerical differences in mean values for accuracy/production tolerance among different manufacturing techniques for both production stages: wax and polymer copings and final pressed glass-ceramic crowns (Table 1a–f). There were no significant differences in mean cement gaps between groups in the marginal area of copings ( $p > .05$ ). In the axial area, additive polymer copings showed significantly smaller cement gaps than milled wax copings ( $p \leq .001$ ) and conventional wax copings ( $p \leq .001$ ). In the occlusal area, both additive polymer copings and conventional wax copings showed significantly smaller cement gaps than milled wax copings ( $p = .002$  and  $p \leq .001$  respectively).

Final crowns showed larger mean cement gaps than wax copings within all three production techniques for all areas except the marginal area within the additive manufacturing technique group. Crowns produced from conventional manual build-up wax copings showed significantly larger mean cement gaps than crowns produced from additively manufactured polymer and milled wax copings in the marginal and axial areas ( $p \leq .001$ ). Among the crowns with smaller cement gaps, crowns produced from additively manufactured polymer copings showed significantly smaller mean cement gaps than crowns produced from milled wax in the marginal and axial areas ( $p \leq .001$ ). In the occlusal areas, the differences in mean cement gaps were only statistically significant between crowns produced from conventional manual build-up wax

**Table 1 – a–f: Results of mean, standard deviation and accuracy, between traditional and digital workflow manufacturing (additive and subtractive production techniques).**(a) Additive production techniques, fit-check polymer burnout, measurement value  $\mu m$ .

Engineering/ Devices	Material	Fit –check	Designed gap <sup>a</sup>	Mean <sup><math>\beta</math></sup>	Mean designed cement gap <sup>a</sup>	SD	SD- cementgap	Accuracy	Mean cement- space <sup>b</sup>
Additive manufacturing Formlabs 2 (N30)	Polymer burn out (Castable V2)	DL0	40	118	78	71	31	78	DL 0–10 = 94
		DL1	40	29	–11	40	0	–11	
		DL2	70	89	19	51	11	19	DL 1–2–8–9 = 67
		DL3	70	167	97	46	6	97	
		DL4	70	218	148	91	51	148	
		DL5	70	142	72	56	16	72	
		DL6	70	122	52	68	28	52	DL 3–4–5–6–7 = 156
		DL7	70	129	59	79	39	59	
		DL8	70	66	–4	49	9	–4	
		DL9	40	83	43	97	57	43	
DL10	40	69	29	111	71	29			

(b) Additive production techniques, fit-check lithium disilicate glass-ceramic measurement value  $\mu m$ .

Engineering/ Devices	Material	Fit –check	Designed gap <sup>a</sup>	Mean <sup><math>\beta</math></sup>	Mean designed cement gap <sup>a</sup>	SD	SD- cementgap	Accuracy	Mean cement- space <sup>b</sup>
Additive manufacturing Formlabs 2 (N30)	Lithium disilicate glass-ceramic	DL0	40	123	83	69	29	83	DL 0–10 = 80
		DL1	40	69	29	72	32	29	
		DL2	70	164	94	89	19	94	DL 1–2–8–9 = 108
		DL3	70	316	246	93	23	246	
		DL4	70	337	267	178	108	267	
		DL5	70	273	203	178	108	203	
		DL6	70	289	219	129	59	219	DL 3–4–5–6–7 = 313
		DL7	70	350	280	142	72	280	
		DL8	70	156	86	102	32	86	
		DL9	40	44	4	56	16	4	
DL10	40	37	–3	60	20	–3			

(c) Conventional production techniques, fit-check burn out wax measurement value  $\mu$ .

Engineering/ Devices	Material	Fit –check	Designed gap <sup>a</sup>	Mean <sup><math>\beta</math></sup>	Mean designed cement gap <sup>a</sup>	SD	SD- cementgap	Accuracy	Mean cement- space <sup>b</sup>
Conventional production techniques (N30)	Burn out wax	DL0	40	115	75	54	14	75	DL 0–10 = 94
		DL1	40	79	39	39	–1	39	
		DL2	40	67	27	58	18	27	DL 1–2–8–9 = 80
		DL3	40	130	90	84	44	90	
		DL4	40	132	92	88	48	92	
		DL5	40	119	79	66	26	79	
		DL6	40	76	36	58	18	36	DL 3–4–5–6–7 = 110
		DL7	40	91	51	53	13	51	
		DL8	40	94	54	54	14	54	
		DL9	40	81	41	43	3	41	
DL10	40	72	32	52	12	32			

(d) Conventional production techniques, fit-check lithium disilicate glass-ceramic measurement value  $\mu$ .

Engineering/ Devices	Material	Fit –check	Designed gap <sup>a</sup>	Mean <sup><math>\beta</math></sup>	Mean designed cement gap <sup>a</sup>	SD	SD- cementgap	Accuracy	Mean cement- space <sup>b</sup>
conventional production techniques (N30)	Lithium disilicate glass-ceramic	DL0	40	239	199	119	79	199	DL 0–10 = 204
		DL1	40	191	151	100	60	151	
		DL2	40	184	144	134	94	144	DL 1–2–8–9 = 181
		DL3	40	375	335	221	181	335	
		DL4	40	309	279	263	223	269	

**Table 1 (Continued)**

(d) Conventional production techniques, fit-check lithium disilicate glass-ceramic measurement value $\mu$ .									
Engineering/ Devices	Material	Fit –check	Designed gap <sup>a</sup>	Mean <sup>b</sup>	Mean designed cement gap <sup>a</sup>	SD	SD- cementgap	Accuracy	Mean cement- space <sup>b</sup>
		DL5	40	355	315	230	190	315	
		DL6	40	355	315	254	214	315	
		DL7	40	447	407	268	228	407	
		DL8	40	201	161	144	104	161	DL 3–4–5–6–7 = 368
		DL9	40	146	106	110	70	106	
		DL10	40	168	128	144	104	128	
(e) Subtractive production techniques, fit-check burn out wax, measurement value $\mu$ .									
Engineering/ Devices	Material	Fit –check	Designed gap <sup>a</sup>	Mean <sup>b</sup>	Mean designed cement gap <sup>a</sup>	SD	SD- cementgap	Accuracy	Mean cement- space <sup>b</sup>
Subtractive manufacturing (N30)	Burn out wax	DL0	40	116	76	74	34	76	DL 0–10 = 88
		DL1	40	85	45	39	–1	45	
		DL2	70	100	30	83	13	30	
		DL3	70	178	108	72	2	108	
		DL4	70	277	207	118	48	207	DL 1–2–8–9 = 112
		DL5	70	178	108	100	30	108	
		DL6	70	206	136	102	32	136	
		DL7	70	233	163	111	41	163	
		DL8	70	156	86	82	12	86	DL 3–4–5–6–7 = 214
		DL9	40	108	68	46	6	68	
DL10	40	60	20	28	–12	20			
(f) Subtractive production techniques, fit-check lithium disilicate glass-ceramic, measurement value $\mu$ .									
Engineering/ Devices	Material	Fit –check	Designed gap <sup>a</sup>	Mean <sup>b</sup>	Mean designed cement gap <sup>a</sup>	SD	SD- cementgap	Accuracy	Mean cement- space <sup>b</sup>
Subtractive manufacturing (N30)	Lithium disilicate glass-ceramic	DL0	40	139	96	64	24	99	DL 0–10 = 115
		DL1	40	100	60	71	31	60	
		DL2	70	151	81	108	38	81	
		DL3	70	319	249	132	62	249	
		DL4	70	352	282	201	131	282	DL 1–2–8–9 = 172
		DL5	70	254	184	111	41	184	
		DL6	70	276	206	102	32	206	
		DL7	70	316	246	76	6	246	
		DL8	70	258	188	116	46	188	DL 3–4–5–6–7 = 303
		DL9	40	177	137	77	37	137	
DL10	40	91	51	57	17	51			

<sup>a</sup> Mean designed cement gap: difference between actual design (designed gap<sup>a</sup>) and outcome design (mean<sup>b</sup>).

<sup>b</sup> Mean cement space for the marginal, internal and occlusal areas.

copings and crowns produced from milled wax where the latter ones showed smaller mean cement gaps ( $p = .025$ ).

## 4. Discussion

### 4.1. Accuracy/Production tolerance and fit

The fit of a restoration is important as it may influence the risk of biological as well as technical complications [1]. It may be especially important for ceramic restorations such as the glass-ceramic crowns in the present study, as they differ from metals in their mechanical properties. Ceramics are brittle and

less tolerant to tensile stresses than metals. Restorations with reduced accuracy and increased cement space will rely on the weak mechanical properties of the cement, rather than the strength of the ceramic adapted to the tooth by a thin but well-established bonding, and may show an increased risk of fracture [12,13]. Ceramic crowns with increased cement thicknesses, as a result of poor fit, have been found to exhibit greater stress at loading [13,14]. An adequate space and well-established bonding will distribute the tensile stress better which has significant influence on fracture resistance [15,16].

The wax copings produced by milling showed larger mean cement gaps than polymer copings produced by additive man-

ufacturing and wax copings produced by conventional manual build-up. Milling is a subtractive technique that has been found to show limitations as the number of axis performing the milling and the size of the milling burs, control precision and fit [7,8]. The largest cement gaps were found in the occlusal area. The part of the occlusal table that is adjacent to the axial walls, the axio-occlusal transition area i.e. measurement points 3 and 7, represent areas where drill compensation may occur [7]. Drill compensation might be one explanation why milled wax copings showed the largest gaps in the occlusal area. Additive manufacturing, such as manual build-up and polymer printing, allow for complex restorations [7,8]. Nevertheless, there may be large variations in production tolerance between different additive manufacturing systems, ranging from 20  $\mu\text{m}$  to 100  $\mu\text{m}$  [17].

The performance of a manufacturing system relative to adaptation and fit is influenced by the restorative material [18]. The present study evaluated pressed lithium disilicate glass-ceramic crowns, which is an increasingly used material for single crowns restorations. Final crowns showed larger mean cement gaps than wax and polymer copings within all three manufacturing techniques. It is not surprising that the gap increases from an early step in production to the final step in production as the initial gap carries through the production steps and adds to the final gap. The crowns produced from the conventional manual build-up wax copings showed larger mean cement gaps than crowns produced from additively manufactured polymer copings and milled wax copings. Ng et al. evaluated the vertical marginal gap of lithium disilicate crowns produced from digital scans, design and milling to crowns produced from manual build-up and pressing using digital photographs in a stereomicroscope. They found significantly smaller overall mean gaps in the digital milled group. Those results correspond in part to our results where digital production showed smaller gaps compared to conventional production in some areas [19]. Zeltner et al. also evaluated lithium disilicate crowns produced from digital scans, design and milled with different systems to crowns produced from manual build-up and pressing using the replica technique. They found that conventionally manufactured crowns revealed better fit than the digitally fabricated crowns regarding internal occlusal areas but no significant differences regarding marginal fit, and concluded that chairside milling resulted in less favorable crown fit than centralized milling production [20]. Neither of these studies included an additive technique however. Homsy et al. compared lithium disilicate inlays produced from manual build-up, milled and printed wax copings [21]. They found that inlays produced from milled wax showed better marginal and internal fit than the other two groups, which is in contrast to some of the findings in the present study where the additive manufacturing technique showed better results in general than the conventional technique. The different geometric design of restorations, which is more complex for inlays compared to crowns yet where the crucial axio-occlusal area sensitive to drill compensation is absent, could explain the different results. In summary, we can conclude that different approaches to methodology and presentation of results have been used which may influence the results and conclusions and make comparisons unreliable.

Most other studies have focused on metal alloys [22]. Among metal-based single crowns, additive manufacturing by laser sintering has been found to show significantly smaller cement gaps than milled crowns [23,24]. However, among metal-based larger restorations, fixed partial dentures (FPDs), the results are conflicting. Örtorp et al. compared cobalt-chrome FPDs produced by subtractive, additive and conventional techniques using digital photographs of cemented and sectioned restorations [7]. They found that FPDs produced by laser sintering showed the smallest cement gaps and milled FPDs showed the largest cement gaps. The study by Örtorp et al. is one of the earliest on the subject of fit of CAD/CAM restorations and the results might be a reflection of limitations in the early subtractive manufacturing. Afify et al. compared marginal discrepancies in milled, laser sintered and cast nickel-chrome FPDs using light microscopy [25]. They found both digital manufacturing techniques, subtractive and additive, showing superior fit compared to the conventional method.

Studies comparing metals and ceramics have also found conflicting results. Batson et al. found that milled zirconia crowns showed the least amount of horizontal marginal discrepancy followed by metal-ceramic crowns made from printed copings and milled and sintered lithium disilicate crowns [26]. They used an impression technique on cemented crowns in situ and evaluated only the marginal area where the present study found no differences between different techniques. Colpani et al. using the replica technique found that metal single restorations showed the best adaptation and suggested that the alloy shrinkage during the metal manufacturing process is uniform and may lead to a superior adaptation [27]. In that study, only oxide ceramics, milled or slip-cast and then glass-infiltrated were evaluated though. Those manufacturing procedures are not consistent with the heat-pressing and sintering of glass-ceramics in Batson et al. and the present study. Milling of oxide ceramics is done oversized to compensate the subsequent sintering shrinkage. Differences in control of this factor could have influence the resultant cement gap in the different studies.

Dahl et al. compared milled, laser sintered and cast FPDs of different materials using superimpositions of scans of the restoration, master model and intaglio surface of the restoration, a triple scan methodology [28]. They found milled FPDs, irrespective if they were metal- or ceramics-based, to show smaller cement gaps compared to cast metal FPDs. However, we can again conclude that different approaches to methodology and presentation of results have been used which may influence the conclusions. Dahl et al. highlighted another factor to be considered when evaluating multi-unit restorations. When comparing the manufacturers' settings for the frameworks with the results actually observed, they found that the observed results always exceeded the manufacturers' settings. The fit of a three-unit FDP is dependent on the fit of both retainers simultaneously. In a multi-unit FDP, there is a possibility that the single retainer is not completely seated because of misfit of one of the other retainers. This fact, in combination with previous findings of large variations in production tolerance between different manufacturing systems, makes for careful interpretation and comparisons of results.

Poor quality production may result in a poor fit and thereby increased risk of complications such as dental caries and loss of retention, two common reasons for the clinical failure of metal ceramic crowns [1]. What constitutes an adequate fit has however not been satisfactorily resolved. Theoretically based goals for cement gap thickness have been suggested to range from 25–50  $\mu\text{m}$  but a gap of up to 120  $\mu\text{m}$  has been judged acceptable based on laboratory- and clinical studies [29,30,31]. The size of gaps are substantially larger than the size of bacteria, but as the spaces are to be filled by the cement they have been considered acceptable. The present study showed differences between the three manufacturing techniques but there were large variations within the subgroups. Most gaps were however within the suggested goals for cement gap thickness or within what has been suggested to be clinically acceptable with some exceptions (Table 1a–f). The largest mean cement gaps were found among the occlusal measurement points whereas marginal and axial areas showed considerably smaller gaps. This is reassuring as it may be hypothesized that an adequate marginal and axial fit will reduce biological complications such as caries, and an adequate axial fit will reduce technical complications such as loss of retention. The reduced fit in the occlusal area may be less critical for the survival of a restoration.

#### 4.2. Methodology — strengths and limitations

The fact that each wax and polymer copings and glass-ceramic crowns, were fitted and measured on their respective epoxy master model is an advantage in the present study as the risk of errors due to wear of a single master model is eliminated. The fact that each final pressed restoration was measured on the same model as its corresponding wax or polymer coping makes comparisons valid.

There are different ways to measure the fit of a restoration as mentioned above. The replica technique contains some practical problems such as the risk of air bubbles present in the interface between light-body and heavy-body and ruptures of the light-body when removed from the abutment [30]. An alternative method is to cement the copings onto the abutments and perform measurements of cement film thickness after sectioning. That technique does not however, eliminate the risk of air bubbles trapped in the cement and it is a destructive technique as the copings are sectioned. The choice of method in the present study was based on the study design. The fit had to be checked in two steps of the procedure and the wax and polymer copings were to be used to produce the final restorations, thus the replica technique was the only option. Furthermore, the replica technique is commonly used and considered a reliable method for the evaluation of marginal and internal fit [32,33] and a recent study comparing the impression replica technique to the cementation technique, found no significant differences and concluded that both techniques may be reliably used for fit evaluation [34]. Studies that analyze the fit of restorations have been found to use different measurement points and focus on different areas of a restoration [22]. Most evaluate the marginal area using 2–4 measurement points. Many also include the internal area and use several measurement points, but few separate between the axial and occlusal area that

constitute the “internal area” [22]. The present study chose to evaluate and compare all three areas, marginal, axial and occlusal, since the different areas may have different impact on clinical performance as discussed above, and also because combining several measurement points, with large variation in size, into one mean value may risk masking significant differences.

The present study is an in-vitro trial. The clinical relevance of the findings must be confirmed by in vivo trials. Few such are available to date however, a recent review identified only three randomized controlled clinical investigations evaluating crowns produced using a digital workflow [35].

## 5. Conclusions

Within the limitations of the present study, it may be concluded that a digital workflow with an additive manufacturing technique produces smaller mean cement gaps in wax and polymer copings and subsequent glass-ceramic crowns, than a conventional workflow or a digital workflow with a subtractive manufacturing technique.

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