

The Accuracy of Fit of Crowns Made From Wax Patterns Produced Conventionally (Hand Formed) and Via CAD/CAM Technology

Keywords

Marginal Gap
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ABSTRACT

Objective: the aim of this study was to compare the marginal and internal fit accuracy of crowns constructed using three different wax production methods: conventional, milled, and 3D printed and utilizing three different cement gap thicknesses.

Methods: 15 identical stone dies were made for each method. Wax patterns were produced and then cast into metal crowns, which were assessed for differences in accuracy of both marginal and internal fit. Measurement points were 4 points per crown: occlusal, axial, marginal gap, and marginal discrepancy points. A silicone impression technique and conventional cementation technique were employed to facilitate the measurements.

Results: there was no significant difference ($p > 0.05$) in accuracy between the digitally and manually produced crowns, with the 3D printed crowns being slightly more accurate. Whereas, statistically significant differences were noticed between the conventional versus printed groups, in occlusal and marginal gap points ($p < 0.05$).

Conclusion: The marginal and internal fit of 3D printed wax patterns is more accurate than the other two production methods. The milling of wax crowns is as accurate as the conventional hand carved production in terms of internal and marginal fit. The manufacturer recommended offset/die-spacer of 30 μ m produced the most accurate internal and marginal fits.

INTRODUCTION

In dentistry, many restorations are still produced using the lost wax casting technique. Lost wax casting involves the production of a wax pattern of the required restoration; this pattern is invested in a heatproof ceramic material. The invested pattern is then placed in a furnace and heated to a high temperature where all wax patterns are burnt out and a void is left in its place, which is later filled with the molten metal of choice. The manual production of good quality dental wax patterns is dependent on the skill of experienced technicians. It is a time consuming procedure with the wax pattern quality dependent on the proficiency of the individual.¹ During the manual production procedure, removing the wax pattern from the die can cause widening of the pattern² and because the wax is glossy, small defects can be difficult to identify.³ Many of different factors can affect the success of dental crowns,² including the accuracy of the fit and seating of the crown.

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A number of theories have been presented to achieve accurate cast crowns. One approach that concerns this study is enhancement of crown seating by making an internal relief inside the cast crown, which will provide a space for the cement.⁴ Provision of a cement space is the most popular method used to reduce marginal discrepancy. The relief can be obtained by two methods, either by subtracting the inner surface to the metal crown, which may affect the accuracy and the final properties of the crown, or by addition of die spacer. The recommended thickness of the die spacer is 40µm^{5,6} and it should be placed 1mm above the margins to ensure good marginal adaptation of crown to tooth.⁷ Small marginal gaps and a good internal fit of dental prosthesis are crucial properties of clinical acceptability and success of dental restorations.⁸ Defective margins on a dental crown can start a chain of problems starting with food accumulation, gingival inflammation, secondary caries, and eventually failure of the restoration and tooth.⁹

The clinically accepted maximum marginal gap is still open to debate; some studies¹⁰ suggested that it should be less than 120µm, whilst other studies consider marginal gap of 150µm to be clinically tolerable.¹¹ Marginal fit consists of marginal gap and absolute marginal discrepancy, where the latter is the misfit between the restoration and the prepared tooth in the vertical and horizontal directions. Large marginal discrepancies might not affect the luting cement when the marginal gap is small, however, it is likely to cause accumulation of debris.¹² The internal fit comprises the axial and the occlusal cement thickness; the internal distribution of luting cement governs the stability and retention of the dental restoration.¹³ Increased cement thickness leads to increased water sorption, hydrolytic breakdown of luting cement^{14,15}, and in time, failure of the overlying restoration under cyclic loading.¹⁶ Thus the internal fit is widely considered alongside the marginal fit when studying the accuracy of dental restorations.¹⁷

In light of the importance of marginal and internal fit, and the need for research of the accuracy of new digital technologies in wax pattern production, the aim of this study was to evaluate the precision of metal crowns produced from wax patterns that were formed by three different production procedures: conventional, production of the wax patterns, wax milling, and 3D wax printing at three different die spacer thicknesses.

The null hypothesis was that there would be no difference between any of the three wax crown production methods and that having no die-spacer/offset would produce poorer fitting crowns than those where a die-spacer/offset was used.

2. MATERIALS AND METHODS

2.1. DIE FABRICATION:

A stone die of an upper right first molar, prepared for a gold crown with a chamfer margin and a convergence angle of 7 degrees was produced. The prepared die was identically duplicated 24 times using a silicone mold (Metrosil Plus, Metrodent, UK)

and die-stone (Esthetic-base gold, Dentona, Germany). The die-stone mixing followed the standard recommendation of 5:1 powder/liquid ratio. The material was mixed in an automatic vacuum-mixing machine (Multivac 4, Degussa, Germany) for 60 seconds, and the final mixture was vibrated into the silicone mold to avoid any air bubble formation. The silicone mold was treated with surface tension reducing agent (Shera-master, Shera, Germany) and dried by air before pouring the die stone. The dies were left to set for 60 minutes and then they were trimmed to have a smooth base.

2.2. WAX PATTERN PRODUCTION

2.2.1. Conventional (hand formed) Production:

Fifteen dies were selected randomly to receive manual wax patterns. The dies were coated with die hardener (George Taub, USA) and blow-dried immediately to avoid any residue on the die surface. The crowns were divided into 3 groups (5 crowns in each group). Different numbers of die spacer (TruFit, George Taub Products, USA) were applied for each group (First group (M1) no die spacer, second group (M2) 4 layers of die spacer = 30µm, third group (M3) 8 layers of die spacer = 50µm). This was done in order to produce a group with the cement gap of 4 layers as recommended for "Tru-Fit" die spacer to give a space from 25 to 30 microns, a group with 8 layers for >50 microns and a group with zero cement gap. The die spacers were applied 1mm from the margin and were applied with two different colours to avoid overlapping of the layers and make it easier to distinguish between them. After the spacer had dried, a separator (Isolit, DegoDent, Germany) was applied and excess was removed by gentle air blowing. The dies were dipped in melted wax (Green, Bego) once and then covered by medium-hard crown wax (Kronenwachs, Bego, Germany) to build up the wax patterns. The anatomical features of the pattern were not accentuated since the focus of the study is on the marginal and internal fit. This was done to prevent any anatomical features preventing identical seating of the cast crowns onto the dies before measurement of marginal fit.

2.2.2. Computer Aided Design and Manufacture (milled and 3D printed methods)

The master die was scanned using Identica Blue scanning machine (Medit, South Korea) and scanning software (Exoscan, Exocad DentalCAD, Germany). The cement gap was set to be 1 mm away from the margin to attain a design as similar as possible to the conventional design. 3 groups were designed with different offsets (5 crowns in each group). The first group (D1) was designed to have no cement space, whilst the second group (D2) was designed to have a cement gap of 30 microns. The literature again recommends the use of 4 layers of die spacer to provide a space of 25 to 30 microns when using Tru-Fit die spacer. The third group (D3) was designed with a cement space higher than the recommended space, i.e. 50 microns. Then the digital design was saved as an stl file and transferred to the milling machine (DWX-50, Roland DG). Five crowns of the same design were then milled from one 14mm wax disc (The Bristol CadCam Co Ltd, UK).

The same digital design was also transferred to the wax printer (3Z Lab, Solidscape, USA). Five identical crowns were then printed on one run of the wax printer. The thickness of each printed layer was set to 45µm. The printed crowns were transferred to heat circulating bath (T100, Grant) under temperature of 48°C to remove supporting wax for ten minutes. The wax patterns were then cleaned and left to dry.

2.2.3. Investing casting the wax patterns and finishing the metal crowns

The wax patterns were all identically sprued using 3mm sprue wax (Bego, Germany). The casting rings were lined with casting ring liner (Trubyte Kaoliner, Dentsply) and sprayed with surface tension reducing agent (Sheramaster, Shera, Germany). Investing material (SheraFina Rapid, Shera, Germany) was mixed according to manufacturer’s instructions. The investment was poured into the investment rings and around the wax patterns with the aid of a vibrator (Pulsar-2, Manfredi, Italy) and left to bench set for 30 minutes. Subsequently, the casting rings were placed in a furnace with a top temperature of 750°C and left to heat soak for approximately one hour. A melting crucible was heated in the casting machine (Multicast Compact, Degussa, Germany) up to 1050°C. Alloy ingots (Phantom-Metal, DeguDent GmbH, Germany) were put into the preheated crucible and heated until molten. The casting ring was taken out of the furnace and seated onto the casting machine (Multicast Compact, Degussa, Germany) where the crucible and casting ring were aligned and the centrifugal casting machine started. Once cast, the casting rings were taken out of the casting machine and put aside to bench cool to room temperature. The cast crowns were de-vested and separated from their sprues and then all identically finished and polished using conventional burs, stones, rubber wheels and polishing wheels.

2.3. MEASUREMENTS OF THE INTERNAL AND MARGINAL GAP

In order to increase the reliability of the measurements, two methods were employed to obtain more points to measure and evaluate as recommended by Nawafleh *et al.* (2013).¹⁷

2.3.1. Measurement Using Silicone Replica Technique

0.3mm of light body VPS impression material (Express™ 2 light Body standard, 3M ESPE) was placed in each crown, and then the crowns were immediately placed on the dies. Pressure was applied using a universal testing machine under cyclic loading from 45N to 50N for 2 minutes (Lloyd LRX tensile tester). Cyclic loading provided a relief for the excess material to escape and ensured even pressure was applied on all samples. The light body impression material inside the crowns was then stabilized and supported using heavy body impression material (Express™ 2 Putty soft 3M ESPE). Once it had set the crowns were removed to reveal the internal silicone replicas.

The resultant impression silicone replicas were sectioned into six pieces; one mesio-distal cut and two bucco-lingual cuts using a sharp scalpel. The pieces were examined under the microscope (SteREO Discovery.V8, Zeiss, Germany) to measure four points on each piece: occlusal, upper axial, lower axial, and marginal gap to make the measurements under magnification of 10x, except for marginal points where 50x was used (Figure 1). AxioVision Software (Zeiss International, Oberkochen, Germany) was employed to make the measurements under magnification of 10x, except for marginal points where 50x was used. Marginal gap measurement followed the technique recommended by Holmes *et al.* (1989)¹².

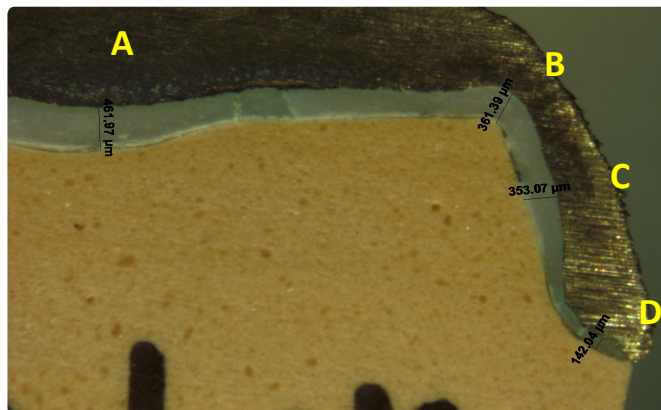


Figure 1: Shows the four points (A occlusal, B upper axial, C lower axial and D marginal gap) measured on each cemented metal coping. All measurements made at a magnification of 10x, except for marginal points where 50x

2.3.2. Measurement Using a Conventional Cementation Technique

The crowns and dies were cleansed thoroughly using steam pressure (Aquaclean 3, Degussa, Germany) and left to bench dry. The crowns were then cemented on the dies using a luting cement (Relyx Luting, 3M ESPE) according to manufacturer’s instructions. The cement was mixed with a cement spatula and loaded into the metal crowns, which were seated on the corresponding dies. The crowns were seated and transferred into a material tester (LRX material tester, Lloyd, UK) to apply a constant pressure of 50N for 3 minutes, which was the recommended setting time of the cement. The crowns were then left for a further 24 hours at mouth temperature (37°C).

The cemented crowns and dies were then sectioned in the midline mesio-distally by a precision saw (Diamond Wafering Blade, Isomet 1000, Buehler, USA) for a maximum of 125 cycle/minute. Each surface was examined under a microscope (SteREO Discovery.V8, Zeiss, Germany) for 10 points of measurement; these were two occlusal, four axial (two on each side of the surface), two marginal gaps, and two marginal discrepancy points. Marginal gap and marginal discrepancy were measured as described by Holmes *et al.* (1989)¹² using AxioVision Software (Zeiss International, Oberkochen, Germany) to make the measurements. Magnification of 10x was generally used, except for marginal area where 50x was used.

2.4. STATISTICAL ANALYSIS

The means and standard error of the mean (SEM) were calculated for each group of results using Microsoft Excel (Office 2010). The statistical package SPSS was used and two-way analysis of variant (ANOVA) was employed in the calculation of statistical significance of differences amongst production groups and measurement techniques. Tukey HSD was performed on the marginal discrepancy group because it was only measured using one technique. The significance level was set to 95%.

3. RESULTS

3.1. RESULTS FROM THE SILICONE REPLICA TECHNIQUE

The mean and the standard deviation of the measured points on each production group are presented in Figure 2. P-values extracted using two-way ANOVA are shown in Table 1(a). Marginal gap and occlusal points values showed significant difference in the hand carved manual procedure versus the printed procedure p-values < 0.05. Axial points values revealed no significant difference amongst the three production procedures. Marginal discrepancy was not measured in this technique because it was difficult to locate the exact outer margin of the crowns.

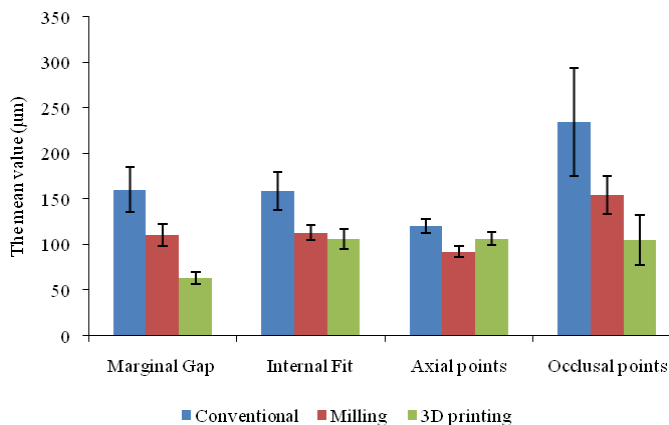


Figure 2: Results in µm from the silicone replica technique: the mean of the different measurement points from different production procedures.

3.2. RESULTS FROM THE CONVENTIONAL CEMENTATION TECHNIQUE:

The mean and the SEM of the measurements from the conventional cementation technique are shown in Figure 3. p-values comparing different production procedures in different points are presented in Table 1(b). The marginal gap and occlusal points of the printing procedure were significantly lower than those of the hand formed manual procedure (p < 0.05). Marginal discrepancy was significantly larger in the milling group than the conventional and printing groups (Figure 4). Figure 5 shows the effect of the precision saw on the metal of the crown and the obliteration of the axial cement space.

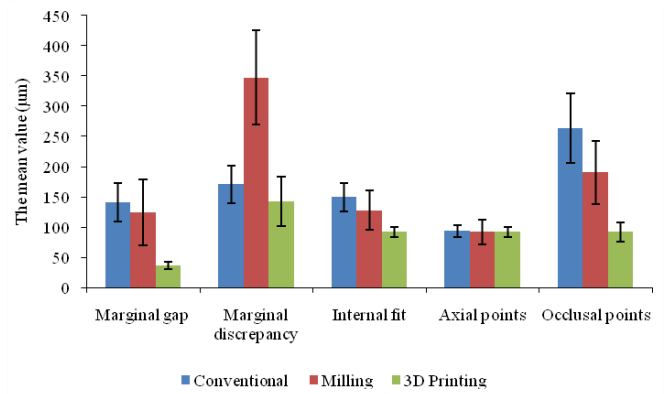


Figure 3: Results in µm from the conventional cementation technique: the mean of different measurement points from different production procedures.

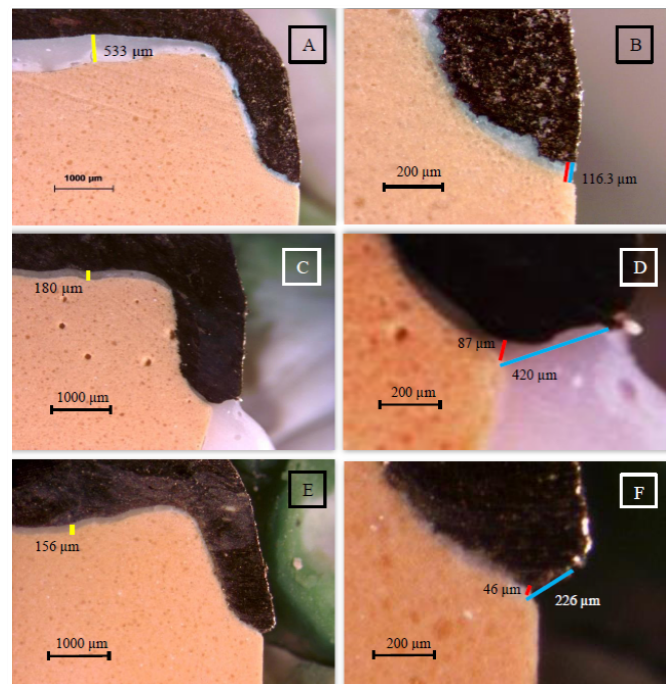


Figure 4: Conventional cementation technique: samples of microscope pictures and measurement points under different magnifications. (A, B) conventional group sample (C,D) milling group sample (E,F) 3D printing group sample; occlusal points (Yellow lines), marginal gap (red lines), marginal discrepancy (blue lines).

Table 1 (a,b). (a) Silicone replica technique: p-values amongst different production procedures on specific points using two-way ANOVA. (b) Conventional cementation technique: p-values amongst production techniques in specific points using two-way ANOVA and Tukey post-hoc tests.

(a)	Marginal gap	Internal fit	Axial points	Occlusal points
Conventional vs milling	0.212	0.103	0.065	0.212
Conventional vs printing	0.014	0.053	0.326	0.041
Milling vs printing	0.233	0.800	0.356	0.443
(b)				
Conventional vs milling	0.985	0.429	0.928	0.241
Conventional vs printing	0.008	0.035	0.938	0.008
Milling vs printing	0.010	0.200	0.988	0.118

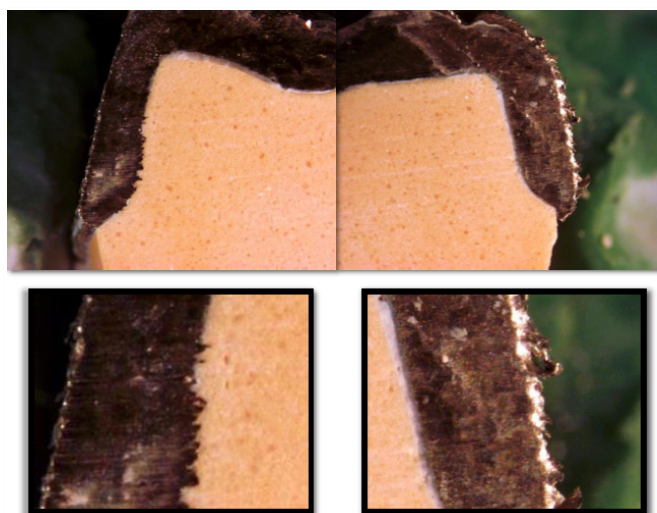


Figure 5: Conventional cementation technique: the effect of precision saw on the metal of the sectioned crowns. (above) two pictures of the same side of a sectioned crown. (below) magnified pictures of the axial walls of the above crown. Notice the drifting of the metal toward the one direction, which obliterated the left axial cement space.

3.3. COMPARISON BETWEEN THE MEASUREMENT TECHNIQUES:

Figure 6 shows the differences between the measurement techniques: the silicone replica technique and the conventional cementation technique. No statistical difference was observed in any of the points.

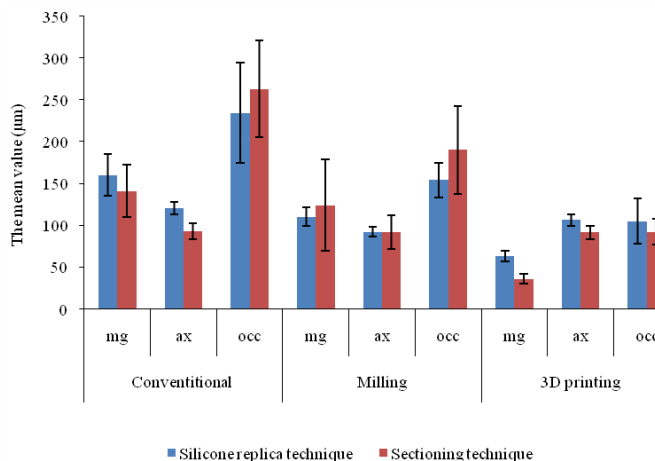


Figure 6: A comparison between the silicone replica technique and conventional cementation technique (µm). There were no statistical significances between the two techniques. (mg) marginal gap. (ax) axial points. (occ) occlusal points.

3.4. MARGINAL GAP:

The manually made crowns of the M2 group (30µm die-spacer) had the best marginal gap, at 111µm±28. The D2 group (30µm offset) had a slightly higher marginal gap of 126µm±43, but with no significant difference between the two (Table 2a).

Eventhough, the crowns produced with the 50µm cement gap resulted in a higher marginal gap than the 30µm cement gap crowns, both the D3 and M3 groups (50µm offset and die-spacer respectively) had a marginal gap that was considered to be clinically acceptable. No statistically significant difference between the digitally produced crowns D3 (50µm offset), and the manually produced ones M3 (50µm die-spacer), were seen (Table 2b). Groups produced with no cement gap resulted in significantly higher marginal gaps compared to the other groups, with the digitally produced crowns, D1 (0 offset) having higher gaps than the manually produced ones but without significant differences (Table 2c). Figure 7 summarises the mean value marginal gap amongst all groups.

Table 2 (a,b,c). Shows the marginal gap of manually and digitally produced metal crowns with 0µm, 30µm and 50µm cement gap

30µm	Marginal gap µm	SD	P Value 0.551
Milling (D2)	126	±43	
Manual (M2)	1113	±28	
50µm	Marginal gap µm	SD	P Value 0.003
Milling (D3)	149	±20	
Manual (M3)	199	±14	
0µm	Marginal gap µm	SD	P Value 0.207
Milling (D1)	311	±99	
Manual (M1)	229	±87	

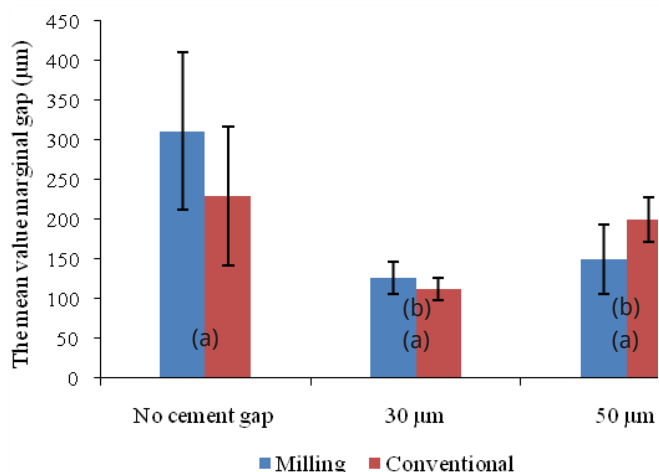


Figure 7: Shows the mean value marginal gap (µm) and the statistical differences between milling and conventional within the three groups. (a) indicates the significant differences (b) indicates no significant differences.

4. DISCUSSION

The aim of this study was to compare the internal and marginal fit of metal crowns made from wax patterns produced by three different procedures

1. Hand formed, manual, production
2. Wax milling
3. 3D wax printing

The hypothesis stated that there would be no difference between any of the three wax pattern production methods and that there would be differences between the die-spacer/offsets used.

The results showed statistical differences between the wax pattern production methods, thereby rejecting the presented hypothesis. The die-spacer/offset methods used showed that the 30µm offset/die-spacer produced smaller internal and marginal gaps than those seen with no offset/die-spacer, thereby confirming the presented hypothesis.

4.1. MEASUREMENT TECHNIQUES

Two measuring techniques were utilized to increase the reliability of the research¹⁷, during which 44 points were measured on each crown; eight crowns for each production method. Increased number of measurement points raises the consistency of the findings¹⁸. The two employed measuring techniques did not yield identical results. Nevertheless, differences between the same measuring points in different techniques were not statistically significant. This is similar to the conclusions of Rahme *et al.* (2008)¹⁹ who found that there was no significant difference between the silicone replica and conventional cementation measurement techniques. However, the conventional cementation technique revealed more significant differences between the three production groups, and therefore the sectioning measurement technique is likely to be a more discriminatory test than the silicone replica measurement technique. Granted, they are both reliable techniques, they are also inherently different and each has its own limitations. The replica technique uses silicone, which has different properties from cements. Silicones are elastomeric materials that are highly accurate; low viscosity silicone impression material can reproduce details of 1-2µm.²⁰ It is susceptible to tear especially in very thin areas like the crown margins in this study. This has resulted in fewer marginal gap points to measure, which might have contributed in different reading of the marginal fit. And even though silicone is dimensionally stable²¹; it is also flexible which made it very difficult to locate the outer point of the crowns margins. The Rely-X luting cement (3M ESPE) is resin modified glass ionomer cement i.e. it is a mixture of polymeric material and salt gel matrix. The different compositions of the silicone and the cement predict different behavior, with the viscosity of a material dependant on its particle size, particle shape, amount and distribution of the applied loading²² and since both techniques are different from the clinical situation where the dies represent teeth, it is not expected to attain identical results from clinical studies. The conventional cementation technique showed inadequacy, when it was noticed that the precision saw had made the metal to drift with the direction of cutting, this might have introduced errors to the readings. This drift of the metal was despite the fact that the saw was set to low cutting speed and water-cooled.

4.2. DIE SPACER AND OCCLUSAL POINTS:

Occlusal points showed the largest values amongst other points with the hand formed, manual, group being the highest, 234±59µm and 263±57µm in both measurement techniques, with significant differences from the printing groups (p-value < 0.05) and non-significant differences from the milling group. This reveals the precision of digital designing of the cement offset i.e. cement space, over the method of manual die spacer application.

The slopes of the prepared cusps of the tooth force the die spacer to accumulate in the surface's grooves and depressions creating layers with unequal thicknesses. Thicker occlusal layers were attained even when extra care was taken by using new liquid with alternating colours to assure the full coverage of each layer. The fact that occlusal cement thickness was the highest in the occlusal surface was also found by several previous studies.²³⁻²⁵

The results of the current study confirm the results of Tsi-trou *et al.* (2007)²⁶ that no significant difference was found between the results obtained using the silicon replica technique and the cross-sectional cementation with resin modified glass ionomer technique. The mean marginal gap in the D2 group (30 µm offset) was 107µm±45 using the replica technique and with cross cementation technique it was 146µm±59, whilst with the M2 group (30 µm die-spacer) the mean marginal gaps for the replica and cross-sectional methods were 116 µm±14 and 107± 53 respectively. The validity of the silicone replica method was confirmed by several studies^{27,19} and since then both the cross-sectional and silicone replica method have been used to evaluate the marginal and internal fit of restorations.

4.3. CONVENTIONAL (HAND FORMED) VS. MILLING PRODUCTION PROCEDURES:

In the silicone replica technique, the marginal gap recorded 160±24µm, 110±11µm in the conventional group and the milled group respectively with no significant difference. Axial and occlusal points did not show any significance either. Similarly, in the sectioning measurement technique, results were comparable with no significant differences; the marginal gap was 141±31µm for the conventional group and 124±54µm for the milling group. These results suggest that conventional hand formed and milling production procedures are not different statistically. This is relevant to the findings of Örtorp *et al.* (2011)²⁵, but conflicting with Vojdani *et al.* (2013).²⁸ This might be due to the following; the higher accuracy of the milling machine that was used in this study compared to the milling machine used by Vojdani *et al.*, (2013),²⁸ (CORiTEC 340i; imes-icore, Germany): the scanning machine used in this study was different from that used by Vojdani *et al.* (2013).²⁸ The higher non-significant results of the conventional group might be due to the fact that operator in this study was less experienced.

Milled wax pattern showed acceptable adaptation within the clinically tolerated margin of the marginal gap i.e. less than 150µm.¹¹ It can be reflected as an efficient, time saving, and reproducible method of wax pattern production that is equal or even better than conventional production in terms of data saving, quality control, and reproducibility. The significantly higher marginal discrepancy, in the milled group can be reasoned by the fact that the original designs of the wax patterns were different; manually, The margins of the wax patterns were made to fit to the tooth margin as accurately as possible, i.e. the wax was flat with no elevation at the margins, but

in the computer design of the milled group the wax patterns were made 200µm thick at the margins.

4.4. CONVENTIONAL (HAND FORMED) VS. PRINTING PRODUCTION PROCEDURES:

In the silicone replica technique, the difference between the marginal gap values of the conventional and printing method was statistically significant, 160±24µm and 63±6 respectively (p-value < 0.05). Similar significant difference was found between the same points using the conventional cementation measurement technique, 141±31µm for the conventional group and 36±5µm for the printing group. The printing group showed excellent adaptation over the internal and the marginal fit. Although axial points did not reveal significant difference between the two production groups, the occlusal points were more accurate (p-values < 0.05) for the printing group. This signifies the accuracy of the printing machine over the conventional hand formed, manual, and production of the wax patterns. And again it might be because of the inexperience of the operator. Nevertheless, this result implies that even an inexperienced technician can produce good fit crowns using the CAD/3D printing technology.

4.5. MILLING VS. PRINTING PRODUCTION PROCEDURES:

Differences between marginal gaps of the milling and printing groups were not significant using the silicone replica technique and significant using the sectioning technique. The reason for this variation of results could be the increased specificity of the sectioning technique when measuring marginal gaps. In contrast, the two measuring techniques showed comparable results for internal fits of the milled and 3D-printing groups with no statistically significant differences. The milled group revealed repeatedly higher values when compared to the 3D-printed group; this advocates the higher accuracy of the printing machine (3Z Lab, Solidscape) over the milling machine (Roland DWX-50). The manufacturer of Roland milling machine displays the accuracy of the machine in its brochure as precise without mentioning the exact accuracy. Whereas, the brochure of the Solidscape printing machine declares that the machine has accuracy of ±25.4µm/mm. This might be due to the fact that the accuracy of the milling machine changes with time following the drop off in sharpness of the used burs, unlike in printing machine, where accuracy is almost fixed when it is working properly.

Differences in the marginal discrepancies were statistically significant, despite the fact that the wax patterns of both groups were from the same digital design. Failure to produce the same result out of the same design implies the inadequacy of one of the production techniques. And because the printed group showed smaller marginal gap and smaller marginal discrepancy, it is suggested that the 3D-printed production is more accurate than the milling machine used here.

5. CONCLUSIONS

Within the limitation of this study, the following points can be concluded:

1. Computer aided design and manufacturing of wax patterns for complete crowns is a reliable procedure that is as good as a conventional hand formed procedure in producing good marginal and internal fit.
2. 3D printing of wax patterns is more accurate than conventional hand formed and milling production of wax patterns in terms of marginal and internal fit.
3. Measurements of internal and marginal fit of metal crowns using the silicone replica technique and conventional cementation technique are similar, however the cementation technique is more specific at the marginal area.
4. A 30µm cement gap (manufaturer recommended) resulted in the most accurate marginal and internal-fit.

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