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Comparison of Marginal and Internal Defects of Indirect Inlay Patterns Fabricated Using Additive Manufacturing and Traditional Methods - An *Ex Vivo* Study

Keywords

Selective Laser Sintering
Computer Aided Design
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ABSTRACT

Introduction: This study aimed at exploring clinical translation of additive manufacturing methods for fabrication of inlay restorations. Materials and methods: On a selected human premolar tooth sample an inlay cavity was prepared. A silicon impression of the tooth was recorded and ten die-casts were poured. Ten inlay wax patterns were fabricated using traditional method. An optical impression of the tooth model was obtained and 20 computer-aided inlay designs were fabricated and optimised for additive manufacturing. Ten models were fabricated by micro-stereolithography and the other ten were fabricated using selective laser sintering. 30 inlay patterns were cast into cobalt chromium metal inlays. For 30 metal inlays, marginal and internal gaps were measured using a silicone-replica-technique, observed under a scanning electron microscope. Results: The measured internal gaps were: Internal-gaps in Conventional lost wax technique (138 ± 8.7), micro-stereolithography (200 ± 7.4) and selective laser sintering (203 ± 11.8). The marginal gaps were: Conventional lost wax technique (162.12 ± 6.8), micro-stereolithography (198 ± 10.3) and scanning laser sintering (203 ± 6.6) Conclusions: The marginal gap and internal gap of a conventional lost wax technique were significantly improved compared with microstereolithography and selective laser sintering (P<0.05). However, according to previous criteria for maximum allowable discrepancy (100 - 200 μm) microstereolithography may represent a potential future alternative for indirect inlay fabrication.

INTRODUCTION

In restorative dentistry, the cardinal motive behind fabricating a prosthesis is to rehabilitate a patient's tooth function.[1] Functionality of a prosthesis depends upon its durability, accuracy of fit and compatibility to oral environment hence, any fabrication method employed must accomplish these requisites.[2] There has been a constant endeavour to introduce newer treatment techniques to minimise errors in adaptation of a prosthesis, as in rehabilitation of lost tooth structure it is one of the leading causes for failure of the treatment.[3,4] To avert these failures attention must be given to shape and fit of restoration for which fabrication method and impression techniques play pivotal roles.[5,6] Conventional lost wax technique (CLTW) of indirect inlay fabrication involves acquiring an impression of prepared tooth surface, preparing positive replica, producing a wax pattern, investment, casting of wax pattern and finally concluding with finishing and polishing of the cast.[7] Though time tested this method comes with certain shortcomings such as risk of inaccuracy due to human error, inherent nature of the materials, laboratory conditions under which they are utilised along with imposed temporal labour, increased production time and cost.[1,8,9] To overcome the above-mentioned hurdles computer-aided design (CAD) came into being, where restorations are designed on a computer-generated virtual optical impression. These virtually designed computer-generated restorations are processed by an automated computer-assisted processing machine.[1] This automated computer processing has two variants, one of which involves subtractive manufacturing where the material is milled into desired shape and size otherwise known as computer-aided milling (CAM) it enables faster production cycles while eliminating human error.[8] The second process follows the dictum of additive manufacturing (AM), where an object is materialised by adding layer upon layer using computerised spatial control.[10] Albeit its advantages CAM falls short on economical and consumable-quality as there is larger consumption of raw materials,[11] and annexed dimensional inaccuracies during the milling process.[12] With the induction of AM, it is being considered as a technological alternative to CAM. To harness AM for fabrication of indirect inlay restorations we devised an experimental workflow which involved acquiring an optical digital impression of the prepared inlay cavity, virtual fabrication of inlay patterns using CAD on computer-generated positive replica of the subject tooth. Followed by optimisation of CAD imagery for three-dimensional (3D) printing, 3D printing of the inlay patterns and subjecting them for casting procedure. For fabrication of a clinically accurate and detailed object through AM, the resolution of a printer plays a pivotal role.[13] Amongst available AM modalities a print resolution of around than 50μ was achievable with Selective LASER sintering (SLS) and Micro-Stereolithography (Micro-SLA)[14] hence, the above-mentioned modalities were considered in the present study. For SLS printer powered pre-polymer of Nylon (DuraForm ProX PA) and for Micro-SLA printer proprietary acrylate based liquid monomer (Visijet FTX) were employed. Both the inks had compatibility with respective printers and satisfied the mechanical properties *(Table 1)* required for inlay patterns such as good tensile strength, abrasion resistant and outstanding dimensional stability. For clinical translation of AM technology into dentistry, identifying the limitations of these latest manufacturing methods in the accuracy of fit is of paramount importance. The null hypothesis was formulated as, there is no difference in the internal and marginal adaption of inlays patterns fabricated using CLTW, Micro-SLA and SLS method.

METHODS AND MATERIALS

Human premolar tooth samples were collected, samples were cleaned-off of superficial debris, calculus, and tissue tags followed by disinfected in thymol solution. Samples were examined for the presence of surface caries and defects. Premolar tooth free of any defects was selected and mounted on acrylic resin blocks. With assistance from an experienced clinician inlay cavity was prepared using carbide burs FG-271 and FG-169L (S.S White dental burs) for a class II mesio-occlusal-distal metal inlay restorations, the preparation design included an occlusal depth of 1.5 mm from the central groove, 1.5-mm deep occlusal box, an isthmus width of 2 mm. The proximal gingival margin was located 1.5 mm above the cementoenamel junction; with 3mm occlusogingival dimension of the proximal box all internal angles were slightly rounded. Ten manual impressions of the tooth sample were obtained with single-step dual viscosity technique using light (Aquasil Ultra XLV Regular Set) and heavy body silicone (Aquasil Ultra Rigid Regular Set).[10] impressions so obtained were poured with die stone Type IV (GC Fujirock) under the manufacturer's instructions. Ten mastercasts were obtained and a coat of approximately 30μ[15] die spacer (Kefoil) was applied on each of them before fabrication of wax patterns. Through experienced technician ten wax patterns were fabricated on their respective master casts. Ten wax patterns so fabricated were designated under conventional lost wax technique (CLWT) group. For remaining two groups, the tooth sample was scanned (ScanIt) *(Figure 1)*. Based on the scanned image 3D computer-aided design (CAD) for the 20 inlays was done (Dental designer premium ver. 2.16.4) *(Figure 2)*, under pre-instructed parameter of a 30μ gap for cement film to compensate for die spacer used under CLTW category.[16] The resultant CAD designs were saved in Standard Tessellation Language (STL) format and relayed to software (Meshmixer ver. 3.3) for optimising CAD images for 3D printing *(Figure 3)*. An STL file is a triangulated approximation of a 3D CAD model, the amount of triangulation in the STL file will affect how faceted (smooth) the surface of the 3D printed object appears. As the number of triangulations increases the image smoothness increases which translates into better print resolution. With the help of Meshmixer software, the image was converted to standard for exchange of product (STEP) format where image smoothness and resolution were enhanced (*figure 4*). After optimising the CAD files in Meshmixer software they were exported to respective printers where 3D images were sliced into multiple 2D layers using the printer software (3D Slicer ver. 4.10), which generates information in the form of Portable Network Graphic images (.PNG format) to feed the information to the printers for printing. Ten inlay patterns were printed using SLS printer (ProX® SLS 6100) (100W power and 10600nm wavelength CO_2 red LASER). In SLS method the printer's LASER heats up the nylon pre-polymer (polyamide) powder just below its melting point fusing the pre-polymer particles together forming a solid object, immediately a new layer of polymer is laid down on the solidified layer by lowering the platform this process of layer by layer sintering and fusing continues till final object is materialised.[13] Object will then be allowed for some time to properly cool off before being removed from the SLS machine. Remaining ten inlay patterns were printed using Micro-SLA (Projet®1200), for this procedure computer-controlled beam projector (200W power and 363.8 nm wavelength Blue LASER) is focused onto the liquid UV curable polymer *(Table 1)*. Sequential layers are added and fused using a binder until the resin pattern is fabricated. The printed patterns are mounted on the UV curing station and photopolymerised for 10 minutes after the photopolymerisation, the patterns are placed under a pressurized water jet which allows any excess binder, unpolymerised resin or supports to be removed.[13,30] Inlay patterns so obtained were subjected for casting. The patterns were placed in the crucible former, covered with a metal ring, and invested in phosphate-bonded investment

(Deguvest-Impact) according to the manufacturer's instructions. After passing through the burnout furnace (Ring furnace, Seki Dental Co.), the Cobalt-Chromium (CoCr) alloy (Remanium) was used for casting in the casting machine (Seki Dental Co., Seoul, Korea), producing 30 metal (CoCr) inlays *(Figure 5)*. To measure the Marginal Gap (MG) and Internal Gap (IG) of the inlays, a skilled dental technician was employed for the silicone replica method. For this technique light-body silicone (Aquasil Ultra XLV Regular Set), was mixed as per manufacturer's instructions and injected between the inlay and the tooth sample, 50N of finger pressure was simulated using a calibrated hydraulic press.[17,18] After hardening, the inlays were separated carefully from the tooth sample, and heavy-body silicone (Aquasil Ultra Rigid Regular Set) was injected into a standard sized circular tray so that the light-body and heavy-body silicone could combine through an even pressure, and embed the light-body silicone. After setting of heavy body silicone the whole impression was carefully retracted. This same procedure was repeated with all thirty inlays and the tooth sample. The 30 silicone replicas so obtained from the above procedure were sliced mesiodistally using a jig (for standardisation) and a surgical blade. The thickness of the light-body silicone replica (corresponds to the gap between the tooth sample and the inlay framework), was measured using a scanning electron microscope (SEM) (Carl Zeiss AG) at 500× magnification (*figure 6*). The MG corresponded to marginal discrepancy at the gingival seat and IG corresponded to internal discrepancy at the axial walls and the pulpal floor. To minimise bias, MG was measured at the edge of the gingival seat (sites 1 and 7). Similarly, IG was noted at five different standardised reference sites; on axial walls the midpoint from axiogingival line to axiopulpal line angle was considered (sites 2 and 6). On pulpal floor firstly, the midpoint of pulpal floor was considered (site 4), the other two sites were marked at the midpoint of axiopulpal line angle and site 4 (sites 3 and 5) (*figure 7*). Calibrations of midpoints were done using the digital gauging tool software (ImageJ software FIJI ver. 1.x) on SEM images. The mean and standard deviation of MG and IG were calculated and the results were analysed through one-way analysis of variance ANOVA using SPSS software version.[23]

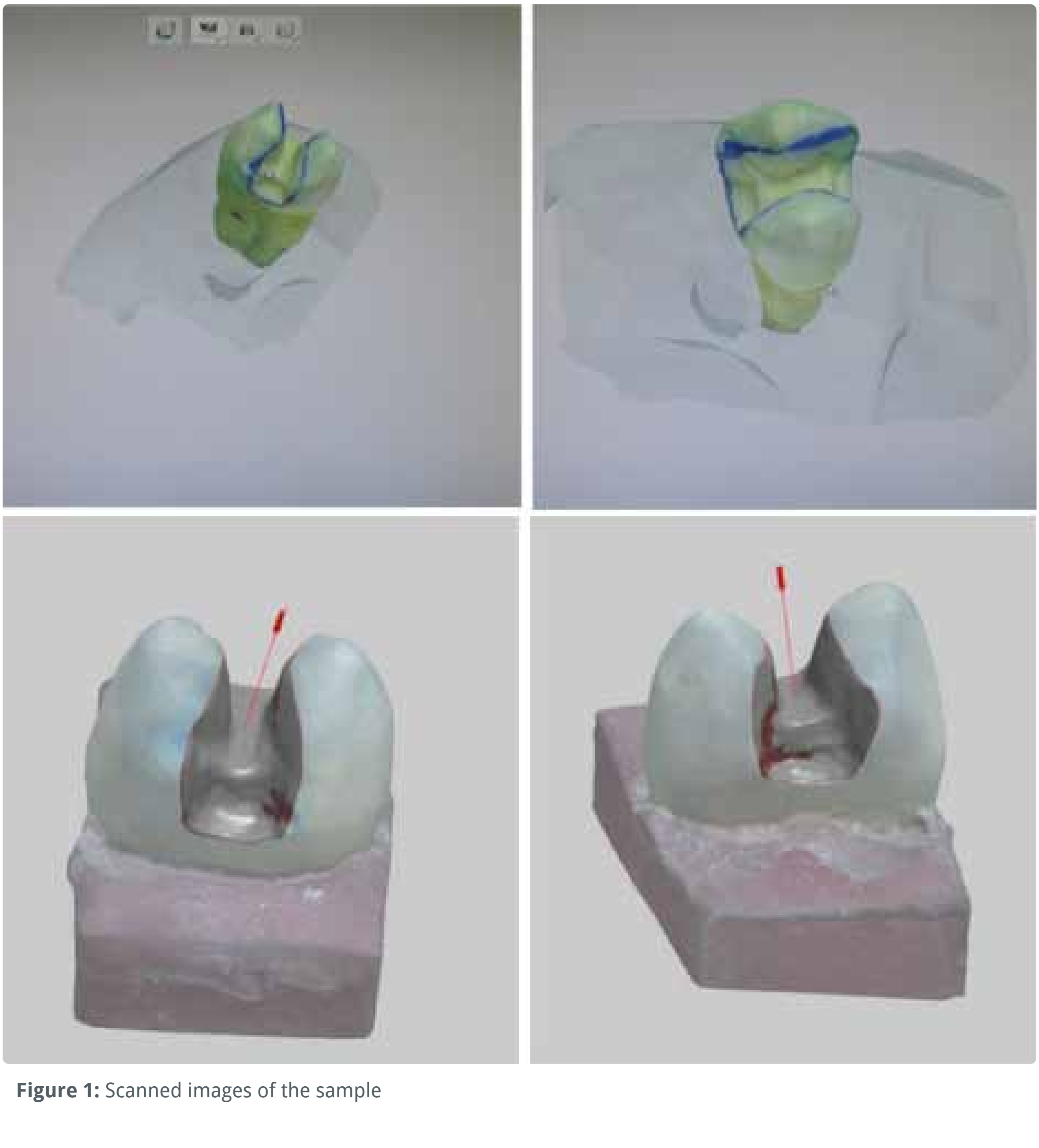

Figure 1: Scanned images of the sample

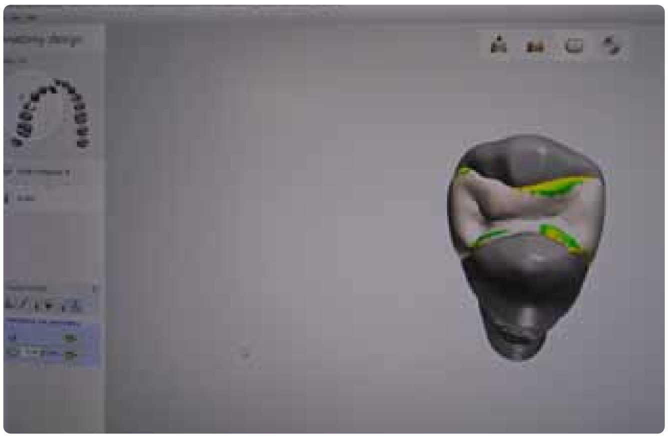

Figure 2: Three dimensional (3D) reconstruction of the inlay patterns

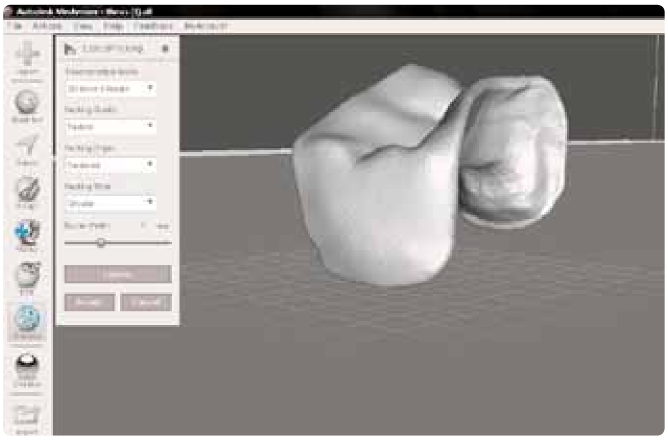

Figure 3: 3D inlay design analysed under Autodesk Meshmixer software

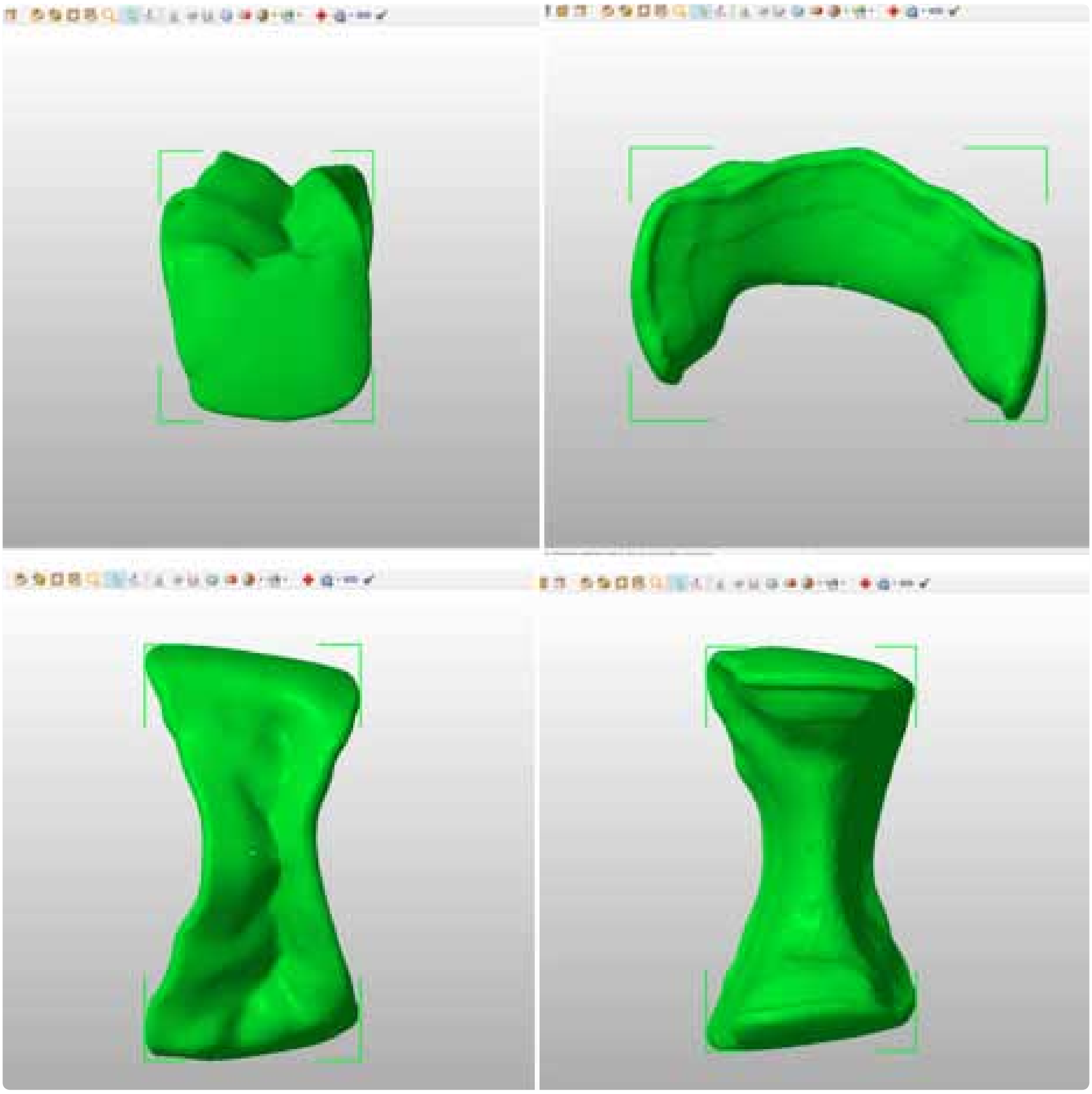

Figure 4: Images converted to standard for exchange of product (STEP) format where image smoothness and resolution were enhanced

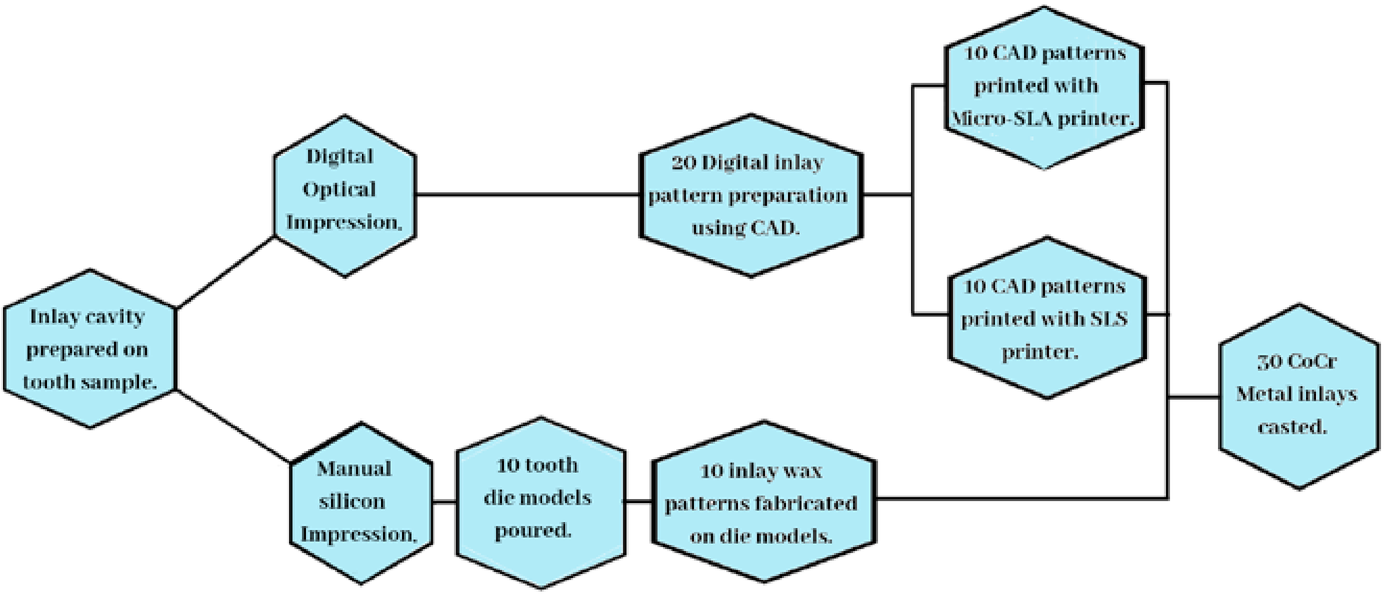

Figure 5: Workflow for conventionally and additively manufactured inlay patterns

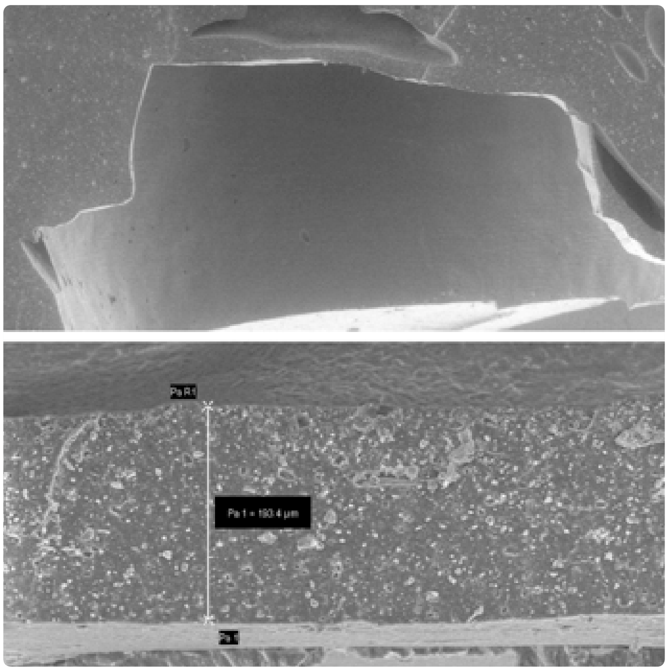

Figure 6: The thickness of the light body silicone replica observed under a scanning electron microscope (Carl Zeiss) at 51X and measured at 500X magnification

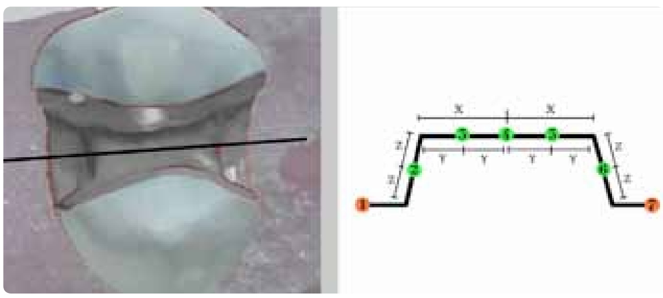

Figure 7: Reference points for measuring discrepancy

RESULTS

The power of the study was found to be 0.991(R) for a sample size of 30 at a global prevalence rate of 3.7% for the incidence of class II caries. A Shapiro-Wilk's test ($p>0.05$) and a visual inspection of their histogrammes, normal Q-Q plots and box plots showed that the MG and IG values were approximately normally distributed for CLTW, Micro-SLA and SLS groups. The value of MG and IG per sample was obtained by calculating the average of readings at sites 1 and 7 and sites 2, 3, 4, 5, 6 respectively. Means and standard deviations were calculated from the average values obtained (*Table 2*). For one-way ANOVA analysis of the means, there was a significant difference in IG and MG according to the manufacturing method ($P<0.05$) thus rejecting the null hypothesis. The results of the post-hoc test using the Tukey HSD method (*Table 3*) showed the IG (137.59 ± 8.74) and MG (162.1200 ± 6.89) were lowest for CLWT method of fabrication and the difference was significant when compared with IG and MG of Micro-SLA and SLS methods. Amongst SLS and Micro-SLA the both IG and MG were lower numerically for Micro-SLA group compared to the SLS group.

DISCUSSION

This study evaluated the MG and IG according to three different fabrication methods, in order to verify the practical applications of AM in clinical dentistry. As the clinical translation of a newer technology demands in vivo functionality and longevity of the prosthesis. The dimensional inaccuracy of an indirect restoration leads to exposure of cement layer at margins and triggers sequelae of deleterious events in the long run. Starting from the dissolution of luting agent, followed by microleakage of bacterial by-products leading to periodontal pathology culminating in physiologic disharmony between the prosthesis and periodontal environment ultimately causing treatment failure.[19,20] In this study the IG and MG showed a significant difference between the three experimental groups.

Table 1. Parameters of the printers used in experimental groups

Parameter	Micro Stereolithography	Selective LASER Sintering
Printer	Projet®1200	ProX SLS 6100
Printer Ink	Visijet FTX Acrylate based liquid monomer	DuraForm ProX PA Nylon based pre-polymer in powdered form
Tensile Strength	30 MPa	43 MPa
Hardness (Rockwell's hardness)	83 D	75 D
Flexural Strength	40 MPa	48 MPa
LASER		
a. Power	200W	100W
b. Wavelength	383.3 nm/Blue LASER	10600 nm/CO_2 LASER
Layer Thickness	0.03 mm	0.08 mm

Table 2. The value of Marginal Gap and Internal Gap per sample in every group was obtained by calculating average of readings at sites 1, 7 and sites 2, 3, 4, 5, 6 respectively. Mean and standard deviation of MG and IG per group is calculated from the available data

	CLWT†	(in microns)	Micro SLA‡	(in microns)	SLS¶	(in microns)
Serial No.	Internal Gap	Marginal gap	Internal Gap	Marginal gap	Internal Gap	Marginal gap
1	135.2	162.1	200.3	195.5	199.5	213.4
2	129.5	177.1	195.9	195.7	201.9	221.6
3	134	165.15	190.7	194.9	209.7	193.3
4	144	157.5	210.4	211.6	205.3	204.7
5	153.9	166.1	196.7	189.7	194.9	189.8
6	135.6	167.15	198.8	183.5	198.2	210.4
7	137.3	157.15	210.4	194.7	202.7	193.1
8	139.7	155.1	191.2	219.4	212.4	208.8
9	144.6	155.55	196.3	198.4	195.6	184.7
10	122.7	158.3	208.8	196.3	213.4	206.3
Mean	137.5900	162.1200	199.9500	198.0100	203.3600	202.6100
Standard Deviation	8.74788	6.89449	7.45792	10.30269	11.81341	6.68634

† Conventional Lost wax technique
‡ Micro-Streolithography technique
¶ Selective LASER Sintering technique

Table 3. Post-hoc test using the Tukey HSD method Technique

Multiple Comparisons						
Dependent variable: Internal Gap						
(I) Technique	**(J) Technique**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval**	
					Lower Bound	**Upper Bound**
1.00	2.00	-62.36000*	4.25600	0.000	-72.9124	-51.8076
1.00	3.00	-65.02000*	4.25600	0.000	-75.5724	-54.4676
2.00	1.00	62.36000*	4.25600	0.000	51.8076	72.9124
2.00	3.00	-2.66000	4.25600	0.808	-13.2124	7.8924
3.00	1.00	65.02000*	4.25600	0.000	54.4676	75.5724
3.00	2.00	2.66000	4.25600	0.808	-7.8924	13.2124
Dependable variable: Marginal Gap						
(I) Technique	**(J) Technique**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval**	
					Lower Bound	**Upper Bound**
1.00	2.00	-35.89000*	3.63673	0.000	-44.9070	-26.8730
1.00	3.00	-41.24000*	3.63673	0.000	-50.2570	-32.2230
2.00	1.00	35.89000*	3.63673	0.000	26.8730	44.9070
2.00	3.00	-5.35000	3.63673	0.320	-14.3670	3.6670
3.00	1.00	41.24000*	3.63673	0.000	32.2230	50.2570
3.00	2.00	5.35000	3.63673	0.320	-3.6670	14.3670

*** The mean difference is significant at the 0.05 level.**

1: Conventional lost wax technique
2: Micro-Stereolithography
3: Selective LASER sintering

The IG and MG in increasing order were CLWT, Micro-SLA and SLS. The difference was emphatically significant when CLWT was compared with Micro-SLA and SLS methods however there was no significant difference between Micro-SLA and SLS methods. Tamac *et al* considered CLWT a gold standard[8] due to its adaptability compared to other manufacturing methods. Micro SLA protocol was numerically closest to CLWT for both MG and IG followed by the SLS method. Amongst the three groups the possible reason for higher discrepancy in SLS and Micro-SLA groups compared to CLTW group could be due to high inaccuracy in replication of virtual die spacer incorporated in CAD models by 3D printers as reported by Hoang *et al.*[21] Hence, higher discrepancy of marginal and internal gaps in SLS and Micro-SLA groups can be attributed to the virtual addition of a 30μ space for cement film thickness in the CAD models to standardise and compensate for the use of spacer in wax pattern fabrication of CLTW method. Another possible confounding could be the impression technique, in the present study for CLTW group a conventional manual silicone impression was recorded, for SLS and Micro-SLA group digital impressions were recorded. Many studies have pointed out reduced accuracy in registering details in digital impression technique compared to the conventional technique.[22,23] This factor might have influenced the results causing a higher discrepancy in SLS and Micro-SLA groups compared to CLTW group. As for CLWT method, the greater discrepancy in marginal adaptation can be multifactorial, as wax patterns were prepared directly onto tooth model there is an element of human error in waxing and distortion at thinner marginal edges while removal of wax pattern.[24] Secondly, procedural flaws such as inadvertent use of excess spacer for preparation of the pattern[24] and lastly it can be also be pointed towards inherent characteristic preferential contraction of wax patterns towards non-bounded side of the restoration from the release of residual pressure after a longer fabrication process.[7,24] In the case of SLS and Micro SLA increased marginal discrepancy compared to internal discrepancy can be attributed to the reason that titanium dioxide powder coating is a necessary prerequisite for scanning which, might exert an influence since the marginal area of the abutments is the spot that is more susceptible to powder accumulation, and therefore could promote a misreading of the scanning procedure. Amongst Micro-SLA and SLS, lesser discrepancy in Micro-SLA is due to higher resolution and surface finish of Micro-SLA printer compared to SLS[25,14] one of the main reasons for higher resolution as suggested by Isheil *et al* is due to the use of blue LASER over red conventional variant which renders higher resolution to the printer due to its smaller wavelength.[26] Another reason can be inclusion intra-layer voids formed during the curing process of SLS method due to the high viscosity of thermally degraded pre-polymer powders (Nylon-12) used as SLS printer's ink which contributes to poor overall dimensional inaccuracy.[27] In case of accuracy in SLS printers, it is dictated by particle size,[28] of the printer ink (nylon polymer) per cured layer. Micro-SLA which uses VisiJet FTX a liquid-based polymer as ink the effect of particle size is negligible. Another possible reason for decreased accuracy in SLS printer could be due to three dimensional inhomogeneous shrinkage of the printed object due to temperature distribution and time-dependant volumetric changes of sintered parts as reported by Shen *et al*.[29] A study by Kim *et al* have reported that SLS has inferior production quality compared to Micro-SLA and lost wax technique,[30] which is in coherence with the present study. For analysis of marginal and internal discrepancy, silicon replica technique was used as its economical and easy to perform.[31] It has certain short-comings such as human error in consistency for the preparation of all analysis sections in similar plane and loci.[32] Possible tear in margins of light body impression while retracting the sample.[32] Despite its disadvantages, Cunali *et al* reported its accuracy in determining discrepancy at par with Micro-computed tomography and certified silicon replica technique as a dependable tool for quantifying marginal and internal discrepancy.[33] For improved resolution and magnification scanning electron microscope with a digital gauging software (ImageJ FIJI ver. 1.x) was used. The clinically allowable range for an indirect restoration's dimensional discrepancy is debatable several longitudinal studies have quoted an acceptable range of 100µ -200µ.[34,35] The overall discrepancy for Micro-SLA was well within 200µ mark, whereas SLS was border-line for the same. Compared to previous parallel studies[6,36] in the present study both marginal and internal discrepancies for inlays are on the higher side, reasons for this shift could be multifactorial. Firstly, choice of the material for casting; compared to previous literature in this study CoCr alloy was tested rather than castable ceramics; poor dimensional accuracy of CoCr alloys casted with lost wax technique has been reported in previous studies.[37] In present study the reason for selecting CoCr alloy over castable ceramics is their cost efficiency and mechanical properties.[38] As it was our chief objective to check the practical feasibility of incorporating economical and efficient 3D printing methods in third world countries where dental treatment procedures are restricted by monetary factors and lack of government schemes for dental insurance.[39] Careful planning of several parameters of the study has been done since there is still no standard protocol for the assessment of fit accuracy of indirect restorations in the literature.[40] In the present study, to avoid error induced through repeated digital scanning of the specimen only a single scan of the tooth specimen was used for fabrication of all twenty CAD models (SLS and Micro-SLA groups).[41] To provide quantified equal pressure in all samples for seating the inlays into the tooth sample a hydraulic press calibrated to 50N force was used. Standardisation of all the mentioned parameters gave a consistency in readings.

CONCLUSION

In conclusion, we would like to state unlike Micro-SLA, SLS's clinical translational validity is questionable which needs further research, revision and evolution in current methods to improvise on the resolution of the printer with better spatial control to achieve desired print quality. In addition, several inevitable possible reasons would have possibly influenced the readings; certain scrutable amends could rectify the increased discrepancy in readings. As a limitation to this study, the effect of different tooth types on the adaptability of restoration needs to be studied, as every tooth variant has specific topographical features which might dictate the outcome. Secondly, the shrinkage dynamics of manufacturing material (polymer, wax) also needs to be taken into consideration for future reference.

MANUFACTURER'S DETAILS

- DuraForm ProX PA; 3D Systems, Rock Hill, SC, USA
- Veroclear; Stratasys Ltd. Rehovot, Israel
- S.S White dental burs; Philadelphia, U.S.A
- Aquasil Ultra XLV Regular Set; Dentsply Caulk, Milford, DE, USA
- Aquasil Ultra Rigid Regular Set; Dentsply Caulk, Milford, DE, USA
- Fujirock; GC dental, Tokyo, Japan
- Kefoil; Keystone Industries, New Jersey, USA
- ScanIt; 3Shape, Copenhagen, Denmark
- Dental designer premium ver. 2.16.4; 3Shape, Copenhagen, Denmark
- Meshmixer software ver. 3.3; Autodesk, California, USA

- 3D slicer ver. 4.10
- ProX® SLS 6100; 3D Systems, Rock hill, SC, USA
- Projet®1200, 3D Systems, Rock Hill, SC, USA
- Deguvest Impact; Degussa-Hüls, Hanau, Germany
- Ring furnace; Seki Dental Co., Seoul, Korea
- Remanium®; Dentauram, Ispringen, Germany
- Carl Zeiss AG, Germany
- ImageJ software; version 1.x, FIJI.

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