Additive *vs.* Subtractive CAD/CAM Procedures in Manufacturing of the PMMA Interim Dental Crowns
A Comparative *in vitro* Study of Internal Fit

KAMEL EARAR[1], ALEXANDRU ANDREI ILIESCU[2]*, GABRIELA POPA[1]*, ANDREI ILIESCU[3], IOANA RUDNIC[4]*, RAMONA FEIER[4]*, RUXANDRA NICOLETTE VOINEA-GEORGESCU[5]

[1]Dunarea de Jos University, Medicine & Pharmacy Faculty, Dentistry Department, 47 Domneasca Str.,800008, Galati, Romania

[2]Craiova University of Medicine and Pharmacy, Dental Medicine Faculty, 2 Petru Rares Str., 200349, Craiova, Romania

[3]Carol Davila University of Medicine and Pharmacy, Dental Medicine Faculty, 19 Calea Plevnei Str., 010221, Bucharest, Romania

[4]Grigore T. Popa, University of Medicine and Pharmacy, Faculty of Dental Medicine, 16 Universitatii Str.,700115, Iasi, Romania

[5]Titu Maiorescu University, Dental Medicine Faculty, 22 Dambovnicului Str., 040441, Bucharest, Romania

CAD/CAM procedures are increasingly used to the manufacturing of 3D-designed PMMA interim dental crowns. The aim of this in vitro study was to compare the internal fit of interim PMMA crowns fabricated by subtractive versus additive CAD/CAM procedures. Starting from a Co-Cr CAD/CAM master abutment model, 20 standardized dental models of dental stone were done by double impression technique. Subsequently two groups of interim PMMA interim crowns, each of them having 10 specimens, were CAM obtained either by milling or 3D printing, using Exocad software package, milling machine Rolland DWX-50, and the 3D printer MoonRay S 100 respectively. An electronic digital caliper Powerfix Profi+ was used for measurements of the chrome cobalt abutment and crowns inner diameter in 4 directions (mesial-distal gingival, buccal-lingual gingival, mesial-distal occlusal, and buccal-lingual occlusal). The null hypothesis that the internal dimensional accuracy of interim PMMA crowns fabricated by DLP additive method would not be different compared to those obtained by milling procedure was rejected since the printed PMMA interim crowns were more accurate. This study concluded that the milled PMMA interim crowns show larger internal dimensional variations than the 3D printed ones. However, the fit variation among interim crowns fabricated by both procedures was statistically non significant, so that both CAM technologies may be equally used in manufacturing process.

Key words: interim crowns, PMMA, milling, 3D printing

Interim crowns, either individual or component of a fixed dental prosthesis, commonly try to ensure the pulp protection in case of prepared vital tooth or to avoid the inadvertent factors that can become risky to bone integration of dental implants recently inserted [1,2]. The dental materials used to manufacture these crowns, regardless their short- or long-term clinical indications, have to demonstrate sufficient chemical and mechanical stability in order to properly accomplish their functional tasks [3-6].

Since many decades the common material used in clinical practice for conventional manually fabricated interim fixed prostheses is polymethylmethacrylate (PMMA). Basically, the internal fit of conventional PMMA interim dental crowns relies on the manufacture methods, either direct or indirect [7,8]. Despite its well-known disadvantages, such as exothermic heat of polymerization and mucosal inadvertent reactions, along with the resin shrinkage that leads to volumetric discrepancies, presently the direct method is still used in dental practice [7,9]. Though the indirect method resulted in an obvious improvement of dimensional stability of interim crowns, being manufactured on stone casts, unfortunately has an important operative shortcoming since it is time consuming [5-7].

However, the experimental and long-term clinical studies of last years strongly suggest that the use of computer-assisted design/computer-assisted machining (CAD/CAM) procedures result in more stable mechanical and chemical properties of PMMA interim dental prostheses. Clinically, in addition to their superior esthetics, the most appreciated outcome is the higher marginal and internal adaptation [1,2,10].

Presently the CAD/CAM procedures allow the manufacturing of 3D-designed PMMA interim crowns either by milling of industrially polymerized PMMA blocks or by using the photopolymer-jetting 3D printing [7,11].

*email:dentalexro@gmail.com; gabrielapopa@yahoo.com; ioana.rudnic@yahoo.com; dr.ramonafeier@yahoo.com

In addition to more stable dimensional properties of PMMA interim crowns and bridges produced by CAD/CAM procedures, the manufacturing of these fixed prostheses is also available in dental office. The modern *chair-side* CAD/CAM technological flow allow in-office fabrication due to the new performing and compact milling machines and 3D printers [11-15].

A short time ago computer-assisted design/computer-assisted machining (CAD/CAM) procedures were launched in manufacturing of interim crowns, initially by using the milling method and afterward the additive techniques [16,17].

The interim PMMA crowns obtained by milling have an improved dimensional stability and mechanical strength as compared to conventional acrylic crowns produced chair-side with conventional direct technique [7]. However sometimes is hard to accomplish a perfect three-dimensional milling due to the bur size and the limits of the motion range of cutter that strongly depends on the number of machine axes [7,13].

The additive method of 3D printing uses a liquid photosensitive resin that is polymerized layer by layer means an ultraviolet light. It allows to manufacturing more complex and smooth prosthetic structures than the milling method and is less material consuming. Presently the additive techniques mostly used to produce interim PMMA crowns are DLP (digital light processing) and PolyJet [7,14-16,18].

The fit of interim crowns was not sufficiently evaluated, and the interest of this issue is increasing due to the permanent improvement of 3D printing technology and the progress in dental photosensitive materials [7,19,20].

The aim of this *in vitro* study was to compare the internal fit of interim PMMA dental crowns fabricated by subtractive versus additive CAD/CAM procedures.

Experimental part

There were used in this *in vitro* study acrylic education models Spofadent® Fantom (SpofaDental). A second lower premolar was prepared by 1.5 mm conventional cutback of occlusal surface, occlusal convergence of axial walls of 6° and a 360° deep chamfer with a 1.0 mm width (fig.1).

The workflow for fabrication of PMMA interim crowns run as follows: silicone impression of prepared abutment (fig.2), stone cast, optical scanning, virtual abutment, milled Co-Cr abutment (fig.3), optical scanning of metal abutment, virtual crown (fig.4), PMMA physical interim crown produced either by milling (fig.5) or 3D printing (fig.6). The scanned data were saved in the format of standard tessellation language (STL), imported in Exocad software package to obtaining the design of virtual abutment (fig.7) and virtual crown (fig.8), and sent the STL files separately by e-mail to milling machine and 3D printer.

Fig.1. Prepared premolar

Fig.2. Silicone impression

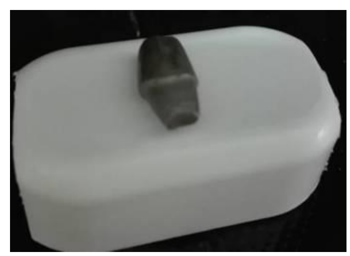

Fig.3. Co-Cr abutment

Fig.4. Virtual crown

Fig.5. Milled crown

Fig.6. 3D printed crown

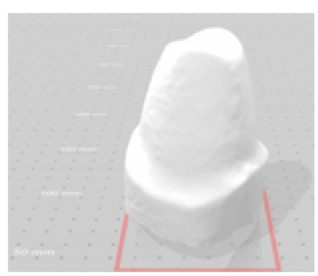

Fig.7. Virtual abutment

Fig.8. Virtual crown

Initially an impression with the double impression technique was performed by using a condensation curing polysiloxane material for precision impression Ormadent Putty(*Major*, Italy) of very high consistency, 75 Shore-A hardness, complying with ISO 4823, Type 0, and Ormamax Regular(*Major*, Italy), a condensation-curing silicone-based material for precision impressions of medium viscosity, complying with ISO 4823, Type 2. The kneading dosage was 0.5 g (0.6 mL) of Ormactivator Gel hardener for 19 g (10 mL) of Ormadent Putty. The paste was positioned in the impression tray within 2 minutes from the start of mixing and pressed on the study model. The impression extraction was done after 10 minutes to allow a proper setting at room temperature. Subsequently a paste composed by Ormactivator Gel catalyst 1 section of catalyst (0.0625 g/0.075 mL) for each dosing section of Ormamax (1.17 g/1 mL) was mixed with a metallic spatula on the mixing block for about 40 seconds. The paste was positioned in the previous impression material (Ormadent Putty) and pressed on the study model within 2 minutes from the start of mixing means of the already used impression tray.

The impression extraction, similar to putty material, was done after 10 minutes to allow its proper setting at room temperature. To obtain maximum precision of the master model the impression was poured within 15 minutes by using dental stone Zhermack – Elite Rock Fast (Zhermack, Italy) sandy brown that was mixed according to the manufacturer recommendations with powder/water ratio 20g/100mL.

The master model was scanned with the laboratory scanner AutoScan-DS200+ (Shining 3D) and following the CAD/CAM procedure finally a chrome cobalt model of prepared tooth abutment was obtained thanks to Exocad software package and milling machine DMP Dental 100 (3D Systems).

20 standardized dental models of dental stone Zhermack – Elite Rock Fast (Zhermack, Italy) were done using same dental laboratory materials starting from 20 impressions of the chrome cobalt model that were done by the double impression technique as aforementioned. Based on Exocad software a virtual anatomic crown of the prepared second lower premolar was designed with 20 μm of cementation space and tight proximal contacts with first premolar and first molar.

The resulted STL files were exported both to the milling machine Rolland DWX-50 and to the 3D printer MoonRay S 100. Rolland DWX-50 is a 5-axis dental milling machine that works X, Y and Z axis, but also can rotates the milled piece through 180º for carving on all its sides (A axis) and tilt it up to 20º on the fifth axis (B axis). MoonRay S 100 (SprintRay) is a 3D printer belonging to DLP additive system family, which provides a 405 nm wavelength blue-violet light with a LED based light source (RayOne UV LED) in order to polymerize a proprietary photosensitive resin. The Z resolution is of 20 μm and the X-Y resolution of 75-100 μm. It shows less than 1% distortion of printed pieces on the build platform. The specimens were cleaned with isopropyl alcohol, dried and placed in a unit for post-processing cycles.

In total 20 PMMA crowns were fabricated using the two different techniques as milled PMMA and 3D printing. In each group were 10 specimens. No further preparations were performed for the inner surface of the crowns. An electronic digital caliper Powerfix Profi+ (OWIM GmbH-AG, Germany) was used for measurements of the chrome cobalt abutment and crowns inner diameter in 4 directions (mesial-distal gingival, buccal-lingual gingival, mesial-distal occlusal, and buccal-lingual occlusal) (fig.9, fig.10).

The statistic data such as means, standard deviation, 95% confidence intervals, one-sample test, and paired samples test were obtained for each CAD/CAM method due to the dedicated statistical software SPSS.

The null hypothesis was that the internal dimensional accuracy of interim PMMA crowns fabricated by DLP additive method would not be different compared to those obtained by milling procedure.

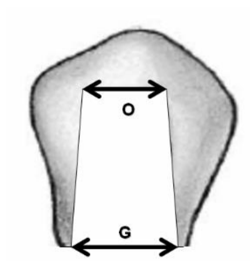

Fig.9. Mesial-distal measurement direction (O occlusal – G gingival)

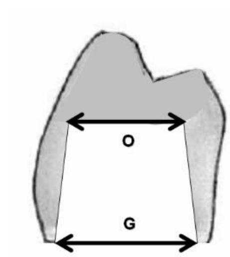

Fig.10. Buccal-lingual measurement direction (O occlusal – G gingival)

Results and discussions

Despite the dimensional differences between milling and 3D printing methods, our results are in consensus with the literature considering that the PMMA interim crowns fabricated by CAD/CAM procedures have an improved accuracy compared to the conventional ones [21-23].

In our study the printed PMMA interim crowns (Table 1) were more accurate than those manufactured by milling (Table 2). Therefore, the null hypothesis was rejected.

Nevertheless, the internal two-dimensional discrepancies in mesial-distal and buccal-lingual directions varied statistically significant ($p<0.05$) within each group of PMMA interim crowns (Table 3).

Our findings showed that there was a more evident impediment in proper fit of interim in mesio-distal directions than in buccal-lingual one in both fabrication procedures. However, the dimensional differences between 3D printed and milled interim crowns were statistically insignificant ($p>0.05$), which suggest that the internal accuracy of both fabrication procedures was within the same range (Table 4).

Considering the drawbacks of milling, based mainly on the cutting burs size, this result might be the consequence of the manufacturing subtractive process that uses solidified polymerized blocks or disks of PMMA. Moreover, the available CAD software to designing the interim crown automatically transforms the point clouds of its virtual image in a machinable one. Accordingly, this mathematical calculation could also result in additional dimensional variations.

Table 1

INNER DIAMETER OF PMMA CROWNS OBTAINED BY 3D PRINTING

Sample no.	GINGIVAL (mm)		OCCLUSAL (mm)	
	B – L	M - D	B - L	M – D
1.	5.90	4.56	4.78	3.79
2.	5.75	4.94	4.51	3.94
3.	5.71	4.85	4.63	3.77
4.	5.69	4.58	4.47	3.74
5.	5.95	4.57	4.51	3.70
6.	5.70	4.68	4.80	3.58
7.	5.95	4.57	4.69	3.67
8.	5.95	4.55	4.88	3.66
9.	5.81	4.67	4.82	3.83
10.	5.76	4.40	4.88	3.78
Mean	5.81	4.63	4.69	3.74
SD	0.110	0.157	0.158	0.100

Table 2

INNER DIAMETER OF PMMA CROWNS OBTAINED BY MILLING

Sample no.	GINGIVAL (mm)		OCCLUSAL (mm)	
	B – L	M - D	B - L	M – D
1.	5.87	4.61	4.41	3.78
2.	5.78	4.73	4.75	3.80
3.	5.74	4.80	4.81	3.72
4.	5.61	4.75	4.80	3.93
5.	5.68	4.89	4.81	3.84
6.	5.95	4.90	4.96	3.83
7.	5.93	4.70	4.75	3.70
8.	5.79	4.78	4.84	3.97
9.	5.80	4.60	4.81	3.72
10.	5.97	4.70	4.94	3.72
mean	5.81	4.74	4.78	3.80
SD	0.118	0.101	0.150	0.093

Table 3

ONE-SAMPLE TEST

	Test Value = 0					
					95% Confidence interval of difference	
	t	Df	Sig (2-tailed)	Mean difference	Lower	Upper
MILLING						
gingiv BL	155.111	9	.000	5.81200	5.7272	5.8968
gingiv MD	147.768	9	.000	4.74600	4.6733	4.8187
occlus BL	100.875	9	.000	4.78800	4.6806	4.8954
occlus MD	129.205	9	.000	3.80100	3.7345	3.8675
PRINTING						
gingiv BL	167.143	9	.000	5.81700	5.7383	5.8957
gingiv MD	93.362	9	.000	4.63700	4.5246	4.7494
occlus BL	93.813	9	.000	4.69700	4.5837	4.8103
occlus MD	117.651	9	.000	3.74600	3.6740	3.8180

Table 4
PAIRED SAMPLES TEST

	Paired Differences							
				95% Confidence interval of difference				
	Mean	SD	St error mean	Lower	Upper	t	df	Sig (2-tailed)
Pair 1								
ging BL Milling Printing	-.00500	.15436	.04881	-.11542	.10542	-.102	9	.921
Pair 2								
ging MD Milling Printing	.10900	.17470	.05525	-.01597	.23397	1.973	9	.080
Pair 3								
occl BL Milling Printing	0.9100	.20480	0.06476	-.05551	.23751	1.405	9	.194
Pair 4								
occl MD Milling Printing	0.5500	.15736	0.4976	-.05757	.16757	1.105	9	.298

The subtractive techniques are less economic since are consuming excessive dental material and do not allow to reuse the discarded milled material, so that they are not environmental friendly. However, it has to be reminded that the additive techinques also need during photo-polymerization an extra-material for the supporting plate of dental crowns [18].

The best fit is accomplished by DLP technique since it generates round two times narrower cementation spaces as compared to conventional procedures to obtaining PMMA crowns [22]. Though among CAD/CAM procedures the milling is less accurate than DLP technique, and both of them superior to conventional method of producing PMMA interim crowns, the value of internal discrepancy resulting in conventional interim crowns is not higher than 120 μm, which is in agreement with the suitable use in patients [1,2,19,22].

Our results also confirm some reports demonstrating that both digital workflows, milling and 3D printing, are rendering sufficient fit of PMMA crowns, as they are within the clinical range [24,25].

The accuracy of a dental impression is characterized by two main parameters: trueness and precision. Since the precision depends on the degree of reproducibility of repeated impressions we proceeded, in our study a metallic Co-Cr abutment of prepared tooth was obtained by CAD/CAM procedure (virtual abutment and physical one, fabricated by milling) in order to be used for multiple *in vitro* impressions. Thus, up to obtaining the physical PMMA crowns by means of CAM procedures, the workflow followed a common pathway that guaranteed the precision of prosthetic pieces [24,25].

Basically, an abutment model is a prerequisite for a tight-fitting interim crown. In daily practice such a crown is fabricated starting from a gypsum model poured from an elastomeric material impression. The precision of impression technique in conventional method largely depends on dimensional stability of the impression material, existing anatomical undercuts and some sensitive steps during dental laboratory processing [24,26-28].

The further use of dental stone models was preferred instead the milled ones was decided since the CAM produced milled abutment models reproduce less anatomical details of the prepared tooth [24-26].

Any digital impression is generating a STL file that is further used within the whole digital workflow for virtual design and physical manufacturing of interim PMMA crowns [29-33]. It was found that throughout the digital flow cumulative error may arise from the optical impression to the manufacturing stage that lead to volumetric discrepancies in final milled or printed dental pieces [29,33].

The fit of interim crowns depends on the size and uniformity of interspace between tooth or implant abutment and the internal wall of the crown. Usually, by means of a software package, the virtual anatomic crown is designed with uniform cementation space of minimum 20 μm. Unfortunately, the method of impression (conventional or digital), die materials, and various dental materials and fabrication procedures of interim crowns, either conventional or CAM (computer-assisted manufacturing), may result in blockages or larger than anticipated gaps that hinder a proper clinical fit [34-37].

However, the CAD/CAM procedures (computer-aided design/computer-aided manufacturing) are extremely promising in dental practice as they avoid numerous complications of conventional methods that could be the cause of improper internal adaptation of interim crown, such as impression transfer to dental laboratory, use of disinfection sprays, delay of pouring the cast, and modeling of the wax patern [34- 36, 39, 40].

Conclusions

Within the limitation of this study, it could be concluded that:

The milled PMMA interim crowns show larger internal dimensional variations than the 3D printed ones produced following DLP technology.

The fit variation among interim crowns fabricated by both procedures was statistically non significant.

Milling and 3D printing by DLP technology may be equally used in manufacturing of interim PMMA crowns for clinical use.

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