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RESEARCH AND EDUCATION

Efficiency of 3D-printed composite resin restorations compared with subtractive materials: Evaluation of fatigue behavior, cost, and time of production

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ABSTRACT

Statement of problem. Three-dimensionally (3D)-printed composite resins have been marketed as materials for definitive restorations. However, limited information is available regarding the stability of the adhesive interface and the efficiency of 3D-printed composite resins.

Purpose. The purpose of this in vitro study was to evaluate the integrity of the marginal adhesive interface before and after thermal and mechanical fatigue of an initial formulation of a 3D-printed composite resin and to evaluate the efficiency of this manufacturing method.

Material and methods. Freshly extracted molars were prepared for onlays and adhesively restored with either 3D-printed composite resin (VarseoSmile Crown Plus) (Group 3D), milled composite resin (Tetric CAD) (Group MCOMP), milled PMMA (Telio CAD) (Group PMMA), and milled lithium disilicate (IPS e.max CAD) (Group EM). Marginal analysis was performed under a scanning electron microscope before and after fatigue by thermomechanical cyclic loading, and initial and terminal percentages of continuous margin (%CM) were compared. The time required for the production of each type of restoration was recorded, and the production costs were also compared.

Results. Before aging, 3D, MCOMP, and EM presented comparable values of %CM (69.8%, 75.9%, and 63.1%, respectively) that were statistically significantly higher ($P<.05$) than those of PMMA (45.1%). After aging, 3D and EM had comparable results (44.7% and 43.7%, respectively), which were lower than those of the MCOMP group (68.5%) but higher than those of the PMMA group (20.5%). Regarding time efficiency, 3D printing took less time than MCOMP or PMMA if more than 8 restorations were fabricated. For the production costs, 3D printing was 5.5, 8.7, and 10.2 times less expensive than PMMA, MCOMP, and EM, respectively. The initial equipment cost was also lower for the additive manufacturing method. However, 3D printing did not always considerably reduce waste.

Conclusions. In terms of marginal adaptation, the evaluated initial formulation of a 3D-printed composite resin behaved similarly to other well-established definitive restoration materials and better than milled PMMA, both before and after fatigue. Three-dimensionally printed resins present advantages in terms of equipment and consumable costs, even for a single restoration, but also for production time when more than 8 restorations were fabricated. (J Prosthet Dent 2022;■:■-■)

Digital dental technologies have progressed rapidly in the last few years, almost 5 decades after François Duret first translated dental arches from analog to digital in 1973 (Duret, F. Empreinte Optique, Lyon 1973). After the well-established advantages that digital workflows provide,[1-5] the focus turned to refining computer-aided manufacturing (CAM) methods and materials.[6-10] While additive manufacturing has been present in dentistry for more than 20 years (Witkowski S, Lange R. Stereolithographie als generatives Verfahren in der Zahntechnik, Schweiz Monatsschr Zahnmed 2003), it has only recently been integrated into dental practice, with more machines and printing materials becoming available.[11] Additive manufacturing can be beneficial when the material is

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Clinical Implications

Three-dimensionally printed composite resins may be an appropriate material for at least long-term interim restorations as they present acceptable marginal adaptation with cost and time advantages.

expensive as it has been reported that less waste is generated.[11] Depending on the number and type of fabricated objects, production time can differ, and either technique can prove advantageous. Also significant are the materials available for additive and subtractive methods, which could be important in terms of esthetics or physical and biomechanical properties.

Recently, 3D-printed composite resins have been marketed as 3-dimensional (3D) printed materials for single-tooth definitive restorations. However, studies on the behavior of these restorations comparing fatigue, time, and cost with subtractive methods are lacking. In addition, studies on the marginal adaptation are also lacking, an important property because many clinical failures are initiated or observed at the transition between the tooth and the restoration, including recurrent caries, stain retention, and water intake that compromise the quality of the restoration.[12]

The goals of the present study were to evaluate the marginal integrity of the adhesive interface of 3D-printed onlays before and after fatigue and to quantify the costs and time of production compared with subtractive CAM restorations. The null hypotheses were that a statistically significant difference would not be found between the marginal integrity, cost, or production time of additive and subtractive CAM restorations.

MATERIAL AND METHODS

Thirty-two freshly extracted human maxillary molars of similar dimensions, without carious lesions or visible root fractures and with a complete root formation, were used for this study in accordance with the Swiss Human Research Act. Standardized extensive onlay cavities were made on the teeth by using coarse diamond rotary instruments (FG 8526; Intensiv), and the margins were finished with fine-grit diamond rotary instruments (FG 3526; Intesiv). The distal surface of the cavities were 1 mm occlusal to the cementoenamel junction (CEJ), and the margins were in dentin, 1 mm apical to the CEJ, in the mesial box to evaluate the behavior of the materials on different tooth substrates. Buccal and lingual cusps were reduced to 3 mm from the CEJ. All internal angles were rounded, and external margins ended in a sharp butt joint finish line (Fig. 1). The cavity surfaces of all specimens were sealed with a layer of the adhesive system (Adhese Universal; Ivoclar AG) and then light polymerized for 20 seconds. A thin protective layer of flowable composite resin (Tetric EvoFlow A2; Ivoclar AG) was applied on the adhesively sealed surface and light polymerized for 20 seconds. The composition of the materials used is presented in Table 1. Enamel surfaces were exposed with fine-grit diamond rotary instruments (FG 3526; Intesiv).

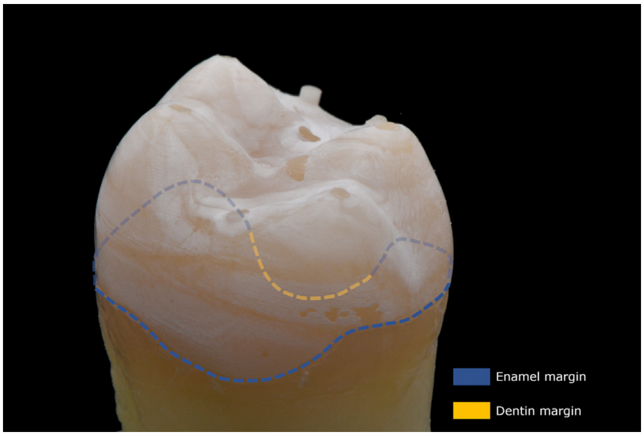

Figure 1. Three-dimensionally printed composite resin specimen before finishing and polishing along cavity outline with margins in enamel and dentin.

Optical scans were made with an intraoral scanner (Cerec Primescan; Dentsply Sirona), and restorations were designed using the corresponding computer-aided design (CAD) software program (Cerec SW 5.1.3; Dentsply Sirona). To standardize the specimens, the same restoration design was copied and applied to all teeth after the definition of the margin. The teeth were then divided into 4 groups (n=8) according to the restoration material: milled composite resin (MCOMP) using an A2 MT shade (Tetric CAD; Ivoclar AG), milled polymethyl methacrylate (PMMA) using A2 LT shade (Telio CAD; Ivoclar AG), milled lithium disilicate (EM) using A2 MT shade (IPS e.max CAD; Ivoclar AG), and printed composite resin (3D) using A2 dentin shade (VarseoSmile Crown Plus; Bego). Onlays were subsequently fabricated either by grinding (MCXL; Dentsply Sirona) or by 3D printing (Sonic Mighty 4K; Phrozen Technology). For the milled restorations, the sprue was positioned palatally, and the fine mode was used. Lithium disilicate restorations were subsequently crystallized according to the manufacturer's recommendations in a sintering furnace (SpeedFire; Dentsply Sirona). For the printed restorations, the parameters were set to a bottom layer count of 6, an exposure time of 4.5 seconds, a bottom exposure of 40 seconds, a lifting distance of 8 mm, and a lift speed of 60 mm/s. The layer thickness of 50 μm was selected, and the restorations were oriented with the occlusal surface toward the build platform, at a 2-mm distance. The Ø0.7-mm supports rested on a 0.8-mm-thick curved foundation. The restorations were cleaned in an ultrasonic bath of 99% isopropyl

Table 1. Study materials

Material	Commercial Name	Composition	Lot Number
Adhesive system	Adhese Universal	10 methacryloyloxydecyl dihydrogen phosphate, 2-hydroxyethyl methacrylate, Bis-GMA, methacrylated carboxylic acid polymer, 1,10-decanediol dimethacrylate, ethanol, camphorquinone, dispersed silica, water	Z01MC6
Flowable composite resin	Tetric EvoFlow A1	Bis-GMA, UDMA (38 wt%), barium glass filler, ytterbium trifluoride, highly dispersed silica, mixed oxide and prepolymers (62 wt%)	Z00WTF
Etching gel	Ultra-Etch	Phosphoric acid 35%	BLXZ5
Ceramic conditioner and primer	Monobond Etch & Prime	Alcoholic aqueous solution of ammonium polyfluoride, silane methacrylate, phosphoric acid methacrylate, and colorant	Z01VLY
Luting composite resin	Tetric Ceram A2	Bis-GMA, TEGDMA, UDMA, barium aluminum fluoroborosilicate glass, silicon dioxide, zirconia oxide, ytterbium trifluoride	Z01B5G
3D-printed composite resin	Varseo Smile Crown Plus	Esterification products of 4,4′ isopropylidiphenol, ethoxylated and 2-methylprop-2enoic acid, silanized dental glass, methyl benzoylformate, diphenyl(2,4,6-trimethyl-benzoyl) phosphine oxide. Total fillers by weight 30-50%	600317
Milled PMMA	Telio CAD	PMMA, pigments, no fillers	Z01WVS
Milled lithium disilicate	IPS e.max CAD	SiO_2, Li_2O, K_2O, MgO, Al_2O_3, P_2O_5, and other oxides	Z01RV6
Milled composite resin	Tetric CAD	Bis-GMA, Bis-EMA, TEGDMA, UDMA, barium aluminum silicate glass, silicon dioxide. Total fillers by weight is 71.1%	Z01VT9

Bis-EMA, bisphenol A ethoxylated dimethacrylate; Bis-GMA, bisphenol A-glycidyl methacrylate; CAD, computer-aided design; PMMA, polymethyl methacrylate; TEGDMA, triethylene glycol dimethacrylate; UDMA, urethane dimethacrylate.

alcohol (IPA) for 5 minutes, thoroughly air dried, and then light polymerized with 1500 flashes from each of the intaglio and occlusal sides of the restorations (Otoflash G171; VOCO GmbH). All restorations were then polished with diamond-coated silicone polishers (OptraGloss; Ivoclar AG).

The resin-based restorations of groups MCOMP, PMMA, 3D, and also the adhesively sealed cavities were then airborne-particle abraded with 27-µm alumina. Exposed enamel surfaces were acid-etched with 35% phosphoric acid (Ultra-Etch; Ultradent Products, Inc) for 30 seconds and then thoroughly rinsed with water for 30 seconds. A layer of the adhesive was applied on both the conditioned restoration and cavity surfaces. A preheated transparent shade light-polymerizing composite resin (Tetric Ceram; Ivoclar AG) was placed into the cavity, and the restorations were seated using an ultrasonic rubber tip (Acteon Satelec C20; Acteon Group). Excess material was removed, and the restoration was exposed to light for 90 seconds per buccal, lingual, and occlusal site with a light-emitting diode (LED) light-polymerizing unit with a >1000 mW/cm^2 irradiance (Valo; Ultradent Products, Inc) checked with a radiometer (Bluelight CheckUp, Bluelight Analytics Inc) at the beginning of each group. For the lithium disilicate onlays, a single-bottle ceramic conditioner and primer (Monobond etch and prime; Ivoclar AG) were used according to the manufacturer's recommendations before the application of the same adhesive system and luting procedure as for the other groups. The margins of the restorations of all 4 groups were then polished with fine-diamond rotary instruments (FG 3526; Intensiv) followed by polishing disks of descending grit (Sof-Lex; 3M).

All specimens were submitted to a mastication simulator (Chewing simulator CS-4; SD Mechatronik) for thermomechanical cyclic loading (TMCL) which consisted of 600 000 masticatory cycles of axial 49-N loads at 1.7 Hz delivered by a Ø4-mm enamel rod to the occlusal surface and 3000 thermal cycles between

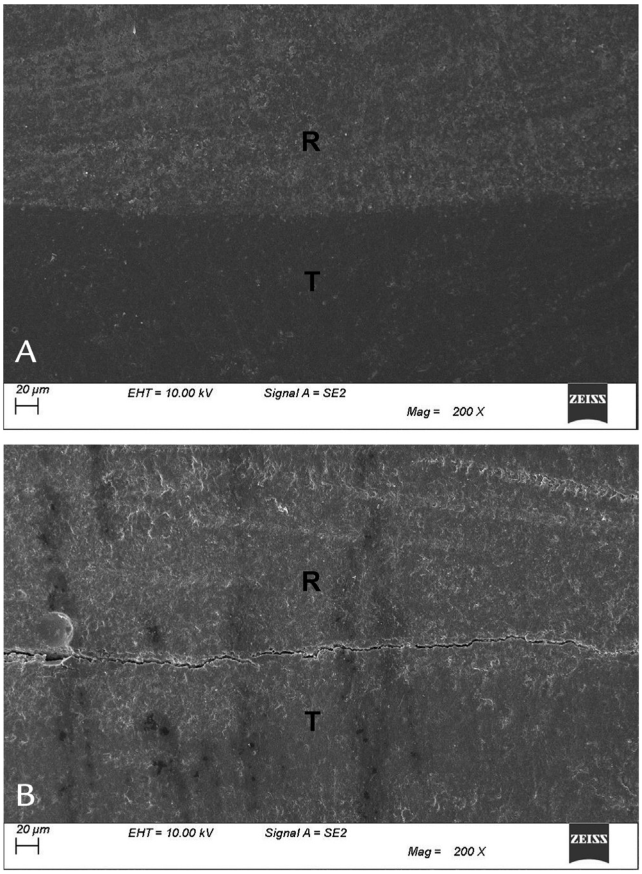

Figure 2. Scanning electron micrographs (original magnification ×200). A, Continuous margin (CM) between 3D composite resin restoration (R) and tooth (T). B, Noncontinuous margin.

Table 2. Required time in minutes for each manufacturing step

Manufacturing Step	3D-Printed Composite Resin	Milled PMMA	Milled Composite Resin	Milled Lithium Disilicate
Printing	64 min (for up to 50 restorations)	–	–	–
Cleaning	10 min (for up to 15 restorations)	–	–	–
Final light-polymerization	8 min (for up to 30 restorations)	–	–	–
Grinding	–	10 min (per restoration)	10 min (per restoration)	10 min (per restoration)
Crystallizing	–	–	–	24 min (for up to 2 restorations)

PMMA, polymethyl methacrylate.

Table 3. Cost of consumables in USD ($)

Consumable	3D-Printed Composite Resin	Milled PMMA Block	Milled Composite Resin Block	Milled Lithium Disilicate Block
3D-printed composite resin	2.9$ (per restoration)	–	–	–
Rinsing alcohol	0.24$ (per restoration)	–	–	–
PMMA block	–	15$ (per restoration)	–	–
Composite resin block	–	–	25$ (per restoration)	–
Lithium disilicate block	–	–	–	30$ (per restoration)
Grinding rotary instruments	–	2.5$ (per restoration)	2.5$ (per restoration)	2.5$ (per restoration)

PMMA, polymethyl methacrylate.

Table 4. Initial investment costs in USD ($)

Equipment	3D-Printed Composite Resin	Milled PMMA Block	Milled Composite Resin Block	Milled Lithium Disilicate
3D printer (new)	1600$	–	–	–
Ultrasonic cleaner (new)	120$	–	–	–
Light-polymerization device (new)	1250$	–	–	–
Milling machine (used)	–	14 000$	14 000$	14 000$
Sintering furnace (used)	–	–	–	6550$

PMMA, polymethyl methacrylate.

5 °C and 55 °C every 90 seconds. Marginal adaptation was evaluated before and after fatigue under a scanning electron microscope (Sigma 300VP; Zeiss) using a custom-made marginal analysis image processing software program (Marginal analysis 4.0; RD). The percentages of continuous margins (%CM) were measured over the whole perimeter of the margin (Fig. 2).

The difference among the 4 groups was evaluated by using a repeated measures analysis of variance followed by post hoc Fisher LSD tests to evaluate pairwise comparisons that have been used to form group ranking according to significative differences. The assumption of normality of the within-cell residuals was assessed using a Shapiro-Wilk normality test, and homogeneity of variances was checked by a Cochran C test. All the analyses were made with a statistical software program (Tibco Statistica 12; Microsoft Corp).

The steps following the design of the restorations and preceding the luting phase were timed by a second independent operator. The cleaning step for the 3D-printing group included the detachment of the supports and the rinsing of the unpolymerized composite resin, and the time dedicated for these 2 steps was added for each 15 restorations. The finishing and polishing were not timed as they were similar among the groups.

Price comparison was performed at 2 levels: the running cost to produce each type of restoration in a solo practice which included the consumables such as the 3D-printing resin and alcohol cleaning solution or the blocks for subtractive manufacturing. On the second level, calculations were made for the average added annual cost of the investment for the equipment such as the 3D printer, the ultrasonic cleaner, the light postpolymerizing device, the milling machine, and the sintering furnace. For the cost of consumables, the prices were obtained from the manufacturer when available or as the average of prices from large dental suppliers (Benco Dental, Henry Schein, Patterson Dental, Net32) accessed in February 2022.

For the 3D-printing group, the tank or the vat containing the composite resin was weighed with a precision top loading balance (PB1502; Mettler Toledo) before and after the printing of the restorations to measure the weight and thus the average price for the fabrication of 1 restoration. The waste factor was then calculated by dividing the final weight of the restorations by the total weight of the used printing resin and then multiplying the result by 100 and subtracting it from 100%. The same waste factor was also calculated for the subtractive method by weighing the restorations and dividing it by the weight of the material in the initial block and discarding the metallic holder.

For the calculation of the average annual cost of the initial investment, the prices of an entry-level liquid-crystal display (LCD) 3D printer (Sonic 4K; Phrozen Technology) with professional postprocessing equipment were all considered to be purchased new. The milling machine and sintering furnace were considered to be purchased used to correspond with the product range of the used 3D printer. The residual price at the end of the life span was considered as half the purchase price for all machines. The life span of the 3D printer was based on 2000 hours of printing before the required replacement of LCD (https://phrozen3d.com/collections/resin-3d-printer-phrozen/products/sonic-mighty?variant=39634923094203#benefits), while the life span of the milling machine was based on

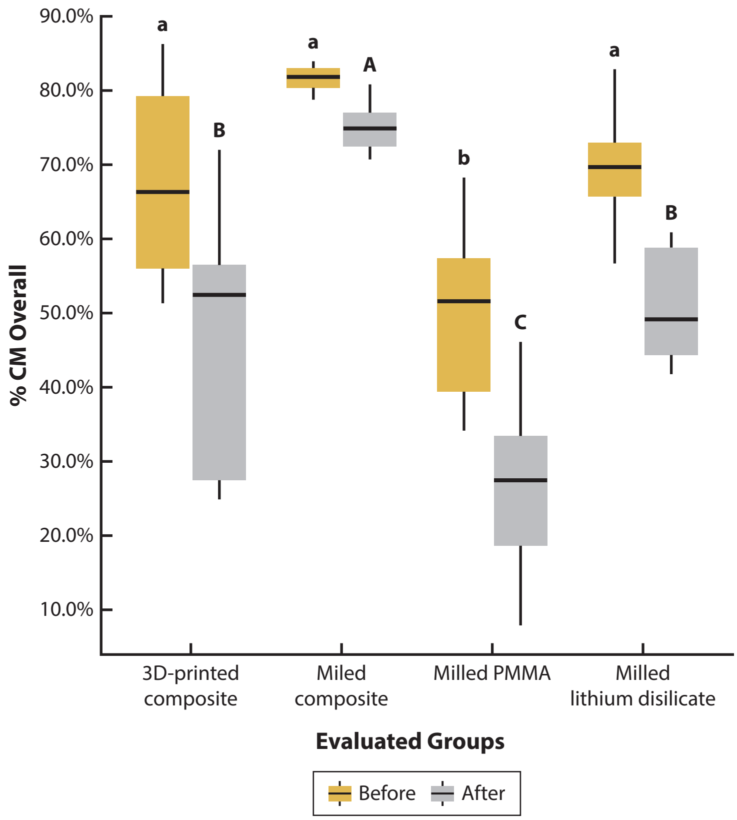

Figure 3. Box plot of continuous margin (%CM) percentages before and after fatigue for all evaluated groups. Different lowercase letters indicate groups with statistically significant difference before fatigue, and different uppercase letters indicate groups with statistically significant difference after fatigue according to Fisher LSD post hoc test. PMMA, polymethyl methacrylate.

2000 restorations before the need to replace the spindle motors. To determine the corresponding time period in years, an average of 20 restorations per month were considered (https://www.dentistryiq.com/practice-management/industry/article/16366837/heres-the-average-number-of-single-crowns-dentists-are-placing-and-where-the-trend-is-headed). Average annual cost=(Initial investment-Residual value)/lifespan.

RESULTS

The recorded times and consumable and investment costs are presented in Tables 2-4. The results of marginal adaptation expressed in %CM, before and after fatigue, are presented in Figure 3. No statistically significant difference (P>.05) was found between the mean %CM before fatigue of MCOMP (75.9%), 3D (69.8%), and EM (63.1%), while PMMA (45.1%) was statistically different from the 3 other groups (PMMA versus MCOMP P<.001, PMMA versus 3D P=.001, PMMA versus EM P=.002) (Table 5). For the analysis after fatigue, MCOMP (68.5%) presented the highest mean %CM, and PMMA (20.5%) showed the lowest values. No statistically significant difference was found between 3D (44.7%) and EM (43.7%) (P=.45).

Table 5. Pairwise comparisons (P-values) between groups before and after fatigue according to Fisher LSD test after repeated measures ANOVA

	Before				After			
Group	3D	MCOMP	PMMA	EM	3D	MCOMP	PMMA	EM
3D	–	.415	.001	.365	–	.002	.002	.449
MCOMP	.415	–	<.001	.088	.002	–	<.001	<.001
PMMA	.001	<.001	–	.017	.002	<.001	–	.014
EM	.365	.088	.017	–	.449	<.001	.014	–

Plots of time and cost estimations for up to 50 restorations are presented in Figures 4, 5. The graphs show that milled PMMA and milled composite resins were the fastest for the production of up to 8 restorations to be manufactured within 1 session. Beyond 8 restorations, 3D printing was more time efficient. For the cost of consumables, 3D-printed composite resin was the least expensive in all situations, while milled PMMA, milled composite resin, and milled lithium disilicate were 5.5, 8.7, and 10.2 times more expensive for the production of 1 restoration. The waste factor was 73% for the 3D printing and 90% for the subtractive method.

For the calculated life span of 8 years, 3D printing incurs an average annual investment cost of 186 USD, while the annual costs for the subtractive methods were

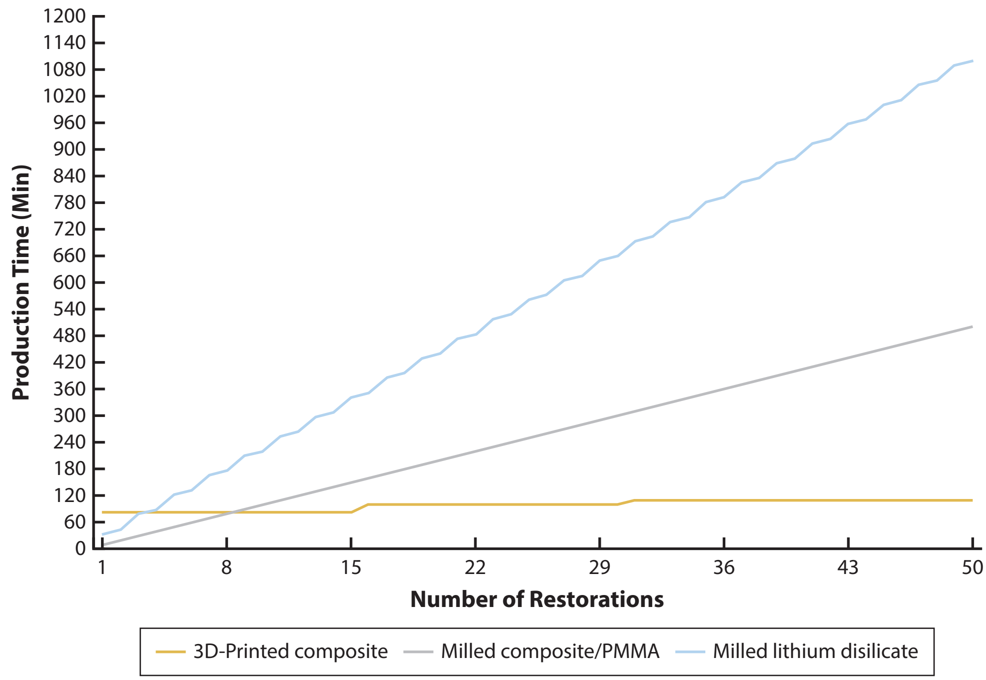

Figure 4. Time of production in minutes of all tested materials in function of number of restorations.

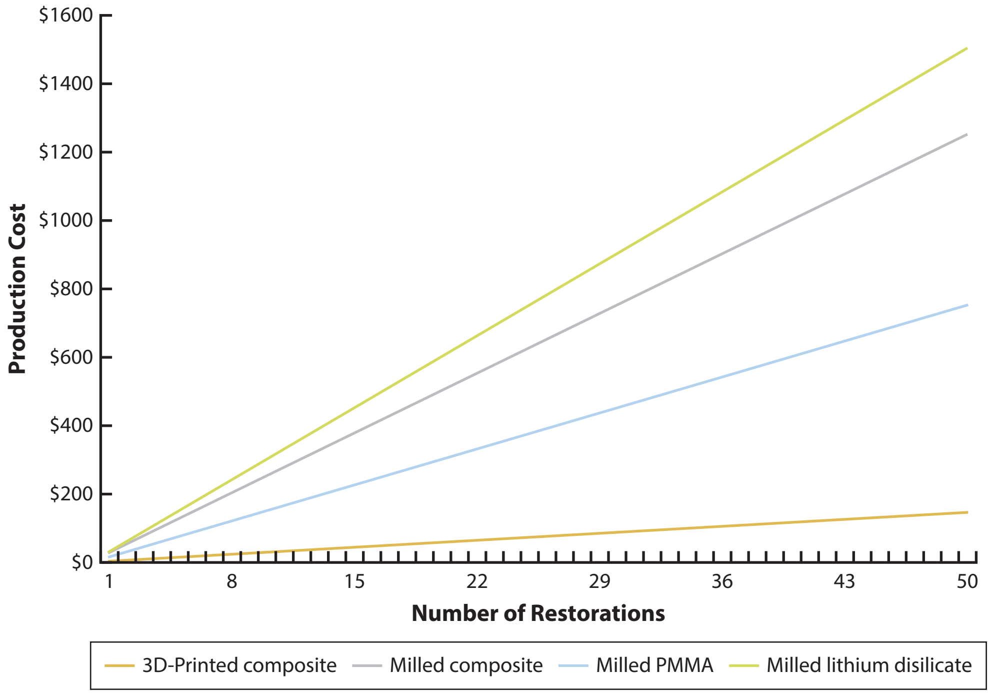

Figure 5. Cost of production in US dollars of tested materials in function of number of restorations. PMMA, polymethyl methacrylate.

875 USD for the milled PMMA and milled composite resins and 1284 USD for the milled lithium disilicate.

DISCUSSION

The first null hypothesis was rejected as significant differences in marginal adaptation were observed between the groups both before and after fatigue. The lower values for the PMMA group were expected as it was selected as a negative control and is contraindicated for definitive adhesive restorations. This material is made of 99.5wt% of industrially polymerized PMMA, with a limited quantity of free radicals available for adhesion, which makes most of the bonding dependent on the chemical link between the methacrylates contained in the restoration and the 10-MDP that is present in most universal adhesives, including the one used in this study. Reduced bond strength to CAD-CAM PMMA materials has been reported previously,[13,14] consistent with the present study. After TMCL, the 3D-printed composite resin and milled lithium disilicate had statistically similar percentages of closed margins. Factors that influence the integrity of the margins after fatiguing include the quality of the bond between the restorative materials and the tooth substrates and also the stress distribution through the interface, which is influenced by the mechanical properties of both the restorative materials and the adhered to dental tissues.[15] Therefore, the results of the marginal integrity show that the investigated 3D-printed composite resin has adhesion comparable with that of the lithium disilicate group and better behavior than the milled PMMA group.

Concerning the running costs, 3D printing was the most advantageous. The material prices may vary slightly with different distributors, but unless the prices drastically change, it will not significantly influence the findings, and the ratios will remain in the same order. However, for the average annual costs of investment, the results may be considerably different as the equipment choices are quite large. Despite being a different class of materials, lithium disilicate was also plotted as it is one of the most commonly used materials to compare it with the composite resin-based alternatives.

It has been reported that 3D printing is a manufacturing process that generates significantly less waste than subtractive methods.[11] In the present study, the waste factor was 73% for the 3D printing, which was not considerably less than the 90% waste of the milled restorations. The waste factor of 3D printing would increase for thinner restorations, and subtractive methods may be even more waste-efficient if block size selection is optimized to the restoration dimension. Therefore, the waste efficiency of 3D printing may be valid for large objects, but not always for small dental restorations. The cost-effectiveness can be explained by the added cost of replacing the rotary instruments in the subtractive method and the current price of the 3D-printed composite resin, which is 1.6 times less expensive than the same weight of PMMA blocks, 2.75 times less than that of composite resin blocks, and 3.3 times less than the price of lithium disilicate. Even if this 3D-printed composite resin is considered only as a long-term interim material, it is still significantly more cost-effective than the milled PMMA alternative.

The physical properties of the investigated 3D-printed composite resin and the other currently available commercial alternatives fall into the class of flowable composite resin with flexural strength ranging from 107 MPa to 130 MPa and an elasticity modulus of around 4 GPa.[16] Therefore, this initial formulation of 3D-printed composite resins requires further evaluation to determine whether the indication for all types of definitive single-tooth restorations is valid. For intracoronal restorations such as inlays and small onlays, it might be acceptable, as some clinical studies investigating flowable composite resins in this indication show good results compared with conventional composite resins.[17-19]

Regarding time efficiency, if the workflow does not allow a batch of 8 restorations for production, subtractive methods remain the faster option. The milling machine used is one of the fastest within the chairside class on the market; thus, considering slower machines would decrease the cutoff point where 3D printing becomes faster for fewer than 6 restorations if a milling time per unit of 15 minutes is considered instead of the recorded 10 minutes in the present study. The printed molar onlays extended 1 mm below the CEJ on one of the proximal sides and can therefore be considered to have the maximum height for single-tooth restorations, which is the slowest to print. If restorations with smaller heights, such as occlusal veneers, are to be printed, the cutoff point will be reduced by 1 for each 1.5-mm reduction in height. Despite having more efficient milling machines than those commonly present in dental offices, the situation would be similar for dental laboratories, with 3D printing becoming more efficient when producing higher quantities.

Beyond the presented results, 3D printing has additional advantages and disadvantages. While it allows for the production of larger span restorations, 3D printers require the handling of unpolymerized resins and cleaning solvents, which may be considered less convenient than the subtractive workflow.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. The quality of the marginal adaptation of the investigated 3D-printed composite resin was comparable with CAM milled composite resins and lithium disilicate before thermomechanical cyclic fatigue.
2. The marginal adaptation was also of similar quality to lithium disilicate after fatigue.
3. The results were also better than those for milled PMMA, both before and after fatigue.
4. Three-dimensionally printed composite resins were more cost-efficient at the production and equipment investment level.
5. Subtractive methods were more time efficient for low production quantities, with 8 restorations in the present experiment.

6. The scope of indications for 3D-printed composite resins is yet to be confirmed, and improving the physical properties of the restorative material would add more value to this manufacturing method.

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