Original paper

Effect of the CAD-CAM and lost-wax framework fabrication techniques on the fracture strength of porcelain in metal-ceramic restorations

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Abstract

Background. Ceramic fracture is a common problem in metal-ceramic restorations (MCRs). The advent of computer-aided design and computer-aided manufacturing (CAD-CAM) technology eliminated the lost-wax technique, which was responsible for many of the problems associated with framework fabrication. However, the role of the CAD-CAM technology in decreasing porcelain fracture is not yet known.

Objectives. The aim of the present in vitro study was to compare the fracture strength of porcelain in MCRs with metal frameworks fabricated with the use of the lost-wax and CAD-CAM techniques.

Material and methods. Twenty metal dies were prepared with a deep chamfer finish line, with a depth of 1.2 mm and the occlusal taper of the walls of 8°, a 2-millimeter occlusal reduction of the functional cusp, a 1.5-millimeter occlusal reduction of the nonfunctional cusp, and the functional cusp bevel. Ten frameworks were fabricated using the CAD-CAM system and 10 with the lost-wax technique. After porcelain veneering, the specimens underwent thermocycling and cyclic loading to simulate the aging process. The load test was then performed. The fracture strength of porcelain was compared between the 2 groups, and the mode of failure was also determined using a stereomicroscope.

Results. Two specimens were excluded from the CAD-CAM group. Thus, 18 specimens were statistically analyzed. The results revealed no significant difference in fracture strength between the 2 groups ($p > 0.05$). The mode of failure was mixed in all specimens from both groups.

Conclusions. Our results indicated that the fracture strength of porcelain and the mode of failure did not depend on the metal framework fabrication technique (lost-wax or CAD-CAM).

Keywords: CAD-CAM, fracture strength, Co-Cr, lost-wax, metal-ceramic

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Introduction

Metal-ceramic restorations (MCRs) are still widely used due to their optimal physical properties and a lower cost as compared to all-ceramic restorations.[1–3] Also, MCRs reportedly have a higher 5-year survival rate than all-ceramic restorations.[4] Evidence shows that dental caries, followed by porcelain fracture and chipping are the main causes of failure of MCRs.[5,6] Several strategies have been suggested to prevent porcelain fracture or chipping in MCRs. Modifying the framework design is one of such strategies.[7]

Cobalt-chromium (Co-Cr) alloys are among the most commonly used alloys for the fabrication of MCRs, with successful clinical application since 1930.[8] Cobalt provides hardness, while Cr enhances the physical properties of the alloy and prevents its corrosion. Molybdenum (Mo), which is also present in this alloy, optimizes other particles, creates space during the solidification process and increases the strength of the alloy. It is also responsible for resistance to corrosion. Tungsten (W) has effects similar to those of Mo on the properties of the Co-Cr alloy and is sometimes used as an alternative to Mo.[8] Such alloys are superior to others, e.g., nickel-chromium (Ni-Cr) ones, and have been recommended for the fabrication of dental prosthetic restorations.[9] Frameworks for MCRs can be fabricated with the lost-wax technique, the computer-aided design and computer-aided manufacturing (CAD-CAM) technology, or the laser sintering technique. Among these, the lost-wax technique is most commonly used.[10] This method was first introduced by Dr. B.F. Philbrook in 1897 and gained popularity in 1906.[11] However, problems that may occur during the investment casting and cooling processes in the lost-wax technique are often responsible for the failure of MCRs, since they can compromise the strength of the bond between porcelain and the metal framework.[12,13] Appropriate metal–porcelain bond strength is imperative for porcelain strength.[14] The advent of the CAD-CAM technology eliminated many problems associated with the use of the lost-wax fabrication technique.[7,15–18] The CAD-CAM technology enables the fabrication of restorations with high precision, irrespective of the length of the restoration.[19]

There are different methods of assessing fracture strength, one of which is the load test. During this test, a load is applied vertically to the sample until fracture occurs, and the mode of fracture is subsequently assessed. It can be adhesive, cohesive or mixed. Fracture is considered adhesive when it occurs at the metal–porcelain interface, and it is considered cohesive when it occurs within metal or porcelain. If both adhesive and cohesive types of fracture are detected in the sample, the mode of failure is considered mixed.[18,20–23]

Previous studies evaluated the effect of different methods of fabrication of Co-Cr frameworks on bond strength, yielding controversial results.[20–24] Considering the gap of information, the purpose of the present study was to compare the fracture strength of porcelain in MCRs with Co-Cr frameworks fabricated with the use of the lost-wax technique and the CAD-CAM technology.

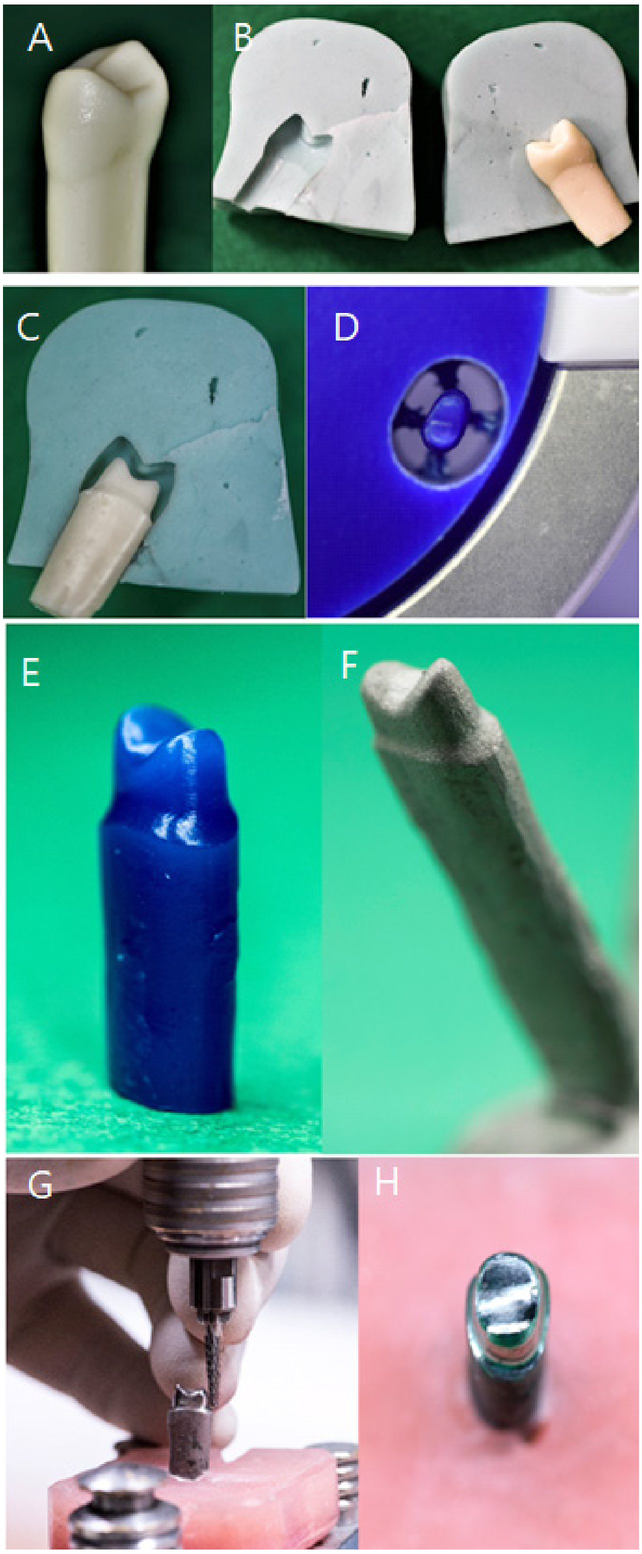

Fig. 1. Cobalt-chromium (Co-Cr) die fabrication

A – maxillary second premolar acrylic tooth; B – putty index prior to the preparation; C – checking the preparation with the use of the index; D – curving the wax block with the use of the computer-aided design and computer-aided manufacturing (CAD-CAM) technology; E – wax pattern of the prepared tooth; F – casting the die; G – modifying the preparation with the use of a surveyor and a dental bur with 4° tapering; H – Co-Cr die.

Material and methods

In this in vitro experimental study, 20 MCRs were fabricated. Ten metal frameworks were fabricated with the lost-wax technique, while another 8 were fabricated using the CAD-CAM technology (2 specimens were excluded).[7,20,25,26] For this purpose, maxillary second premolar acrylic teeth received deep chamfer preparation at the cervical region all-around, with a depth of 1.2 mm, the occlusal taper of the walls of 8°, a 2-millimeter occlusal reduction of the functional cusp, a 1.5-millimeter occlusal reduction of the non-functional cusp, and the functional cusp bevel.[24] Acrylic teeth were then scanned with a Ceramill Map 400 scanner (Amann Girrbach, Pforzheim, Germany) and the information was sent to a Ceramill Motion 2 milling machine (Amann Girrbach). Based on this information, wax blocks (Yamahachi Dental, Gamagori, Japan) were carved and sprued. The metal die was invested with phosphate-bonded investment (Z4 Universal Investment; N&V Belgium, Sint-Niklaas, Belgium) and cast using a Ducatron Quattro casting machine (Ugin Dentaire, Seyssinet-Pariset, France) and the Co-Cr alloy (Magnum Ceramic Co; Mesa Italia, Travagliato, Italy).[15,27,28] The die was then prepared with a tapered bur on a surveyor (Fig. 1). The prepared metal die was scanned and the scan data was transferred to the CAD software in a Ceramic Mind CAD workstation (Amann Girrbach). After assessing the finish line and ensuring that there were no undercuts, the framework was designed with an equal thickness of 0.5 mm, and a die spacer of 50 µ at a 1-millimeter distance from the finish line (Fig. 2).[7,23]

Fabrication of specimens with the lost-wax technique

A CAD-CAM machine was used to increase accuracy, and also for the standardization of specimens. The data regarding the framework design was transferred from the Ceramill Mind CAD workstation to the communicating milling machine (Ceramill Motion 2) and 10 wax patterns were carved out of the wax disks (Fig. 3A,B).[7,24] Next, the specimens were sprued and invested using phosphate-bonded investment (Z4 Universal Investment).

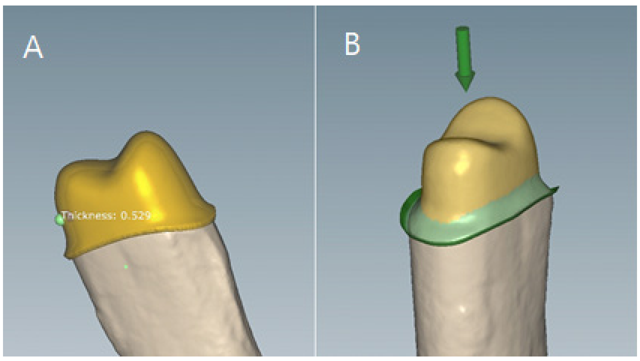

Fig. 2. Die spacer of 50 µ at a 1-millimeter distance from the finish line (A) and the fabrication of a framework with a thickness of 0.5 mm (B)

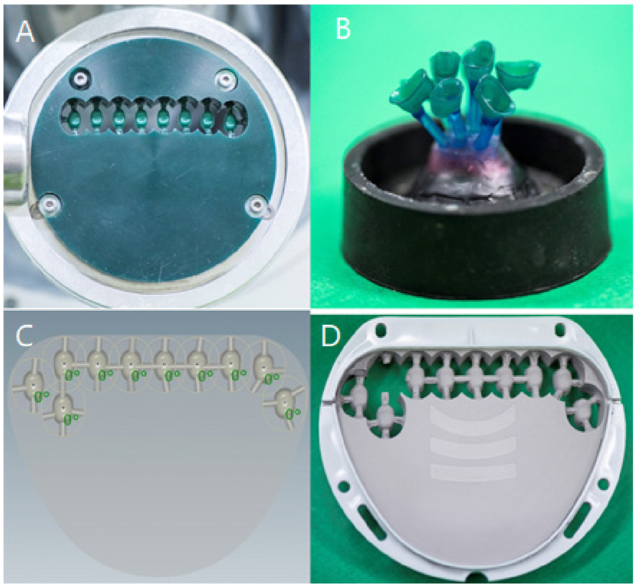

Fig. 3. Framework fabrication with the lost-wax technique (A,B) and the CAD-CAM technique (C,D)

Fabrication of specimens with the CAD-CAM technique

The data regarding the framework design was transferred from the Ceramill Mind CAD workstation to the communicating milling machine (Ceramill Motion 2). Next, 8 specimens were dry-milled by using Co-Cr blocks (Ceramill Sintron blanks; Amann Girrbach) (Fig. 3C,D).[7,20,24] The specimens were then sintered in a Ceramill Argovent 2 sintering compartment (the Ceramill Argotherm 2 system; Amman Girrbach), in an atmosphere of argon gas at 1,280°C for 6 h. The specimens were all homogenous and had no distortions. For surface treatment prior to veneering, according to the manufacturer's instructions, the specimens in the lost-wax group were sandblasted with 150-micrometer aluminum oxide particles, while the specimens in the CAD-CAM group were sandblasted with 50-micrometer aluminum oxide particles for 20 s at an angle of 45° and a distance of 10 mm, under pressure of 3 bars (Basic eco micro-blaster; Renfert, Hilzingen, Germany). All specimens were subsequently cleaned with 80% ethanol in an ultrasonic bath for 5 min, and then placed in a furnace for oxidation and degaussing (Programat P310; Ivoclar Vivadent, Schaan, Liechtenstein).[7,22,23] The thickness of all specimens was measured with a digital caliper with an accuracy to 0.01 mm. Table 1 shows the information regarding the alloys used in the lost-wax and CAD-CAM techniques.

Porcelain veneering

To standardize the shape and amount of porcelain in all specimens, a full-contour crown was designed using the Ceramill Mind software and carved out of a wax block.

Table 1. Chemical and mechanical properties of the alloys used for the fabrication of frameworks with the lost-wax and CAD-CAM techniques

Properties	Magnum Ceramic Co					Ceramill Sintron				
	Co	Cr	Mo	W	Si, Fe, Mn	Co	Cr	Mo	W	Si, Fe, Mn
	64%	21%	6%	6%	~3%	66%	28%	5%	–	~1%
Yield strength [MPa]	570					450				
Modulus of elasticity [MPa]	194					200				
Elongation at fracture [%]	10					30				
Vickers hardness (HV 10)	286					270				
CTE (25–500°C) [$°C^{-1}$]	14.1×10^{-6}					14.5×10^{-6}				
Density [g/cm^3]	8.8					7.9				

CTE – coefficient of thermal expansion; Co – cobalt; Cr – chromium; Mo – molybdenum; W – tungsten; Si – silicon; Fe – iron; Mn – manganese.

A putty index (Speedex; Coltène/Whaledent, Altstätten, Switzerland) was made based on the wax model. Two layers of paste (InLine Opaquer A3; Ivoclar Vivadent) were applied to all specimens, and then the porcelain body (InLine Dentin A3; Ivoclar Vivadent) was applied using the silicon index (Fig. 4). Lastly, the specimens were glazed (Fig. 5). One technician performed all the baking procedures according to the manufacturer's instructions (Ivoclar Vivadent).

Simulation of oral conditions

All specimens underwent thermocycling and cyclic loading to simulate normal oral conditions. The specimens

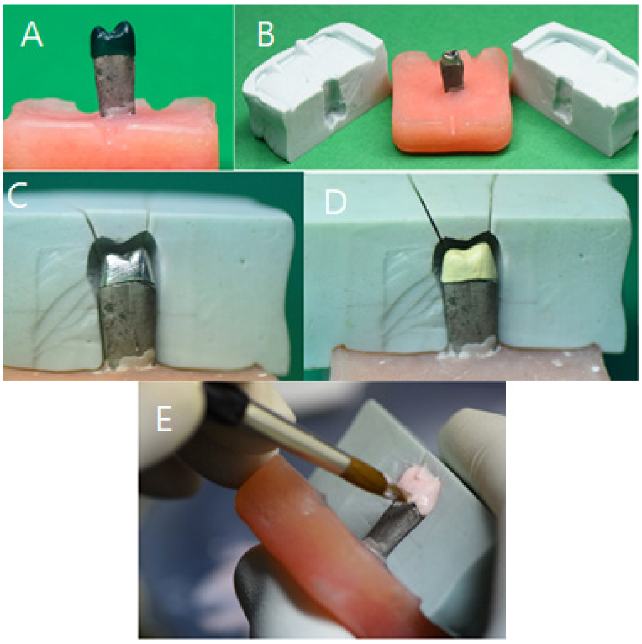

Fig. 4. Porcelain veneering procedure

A – fabrication of a full-contour wax model; B – preparation of a silicone index; C – Co-Cr metal framework; D – placement of a layer of paste on the metal framework; E – placement of the porcelain body, using the silicone index.

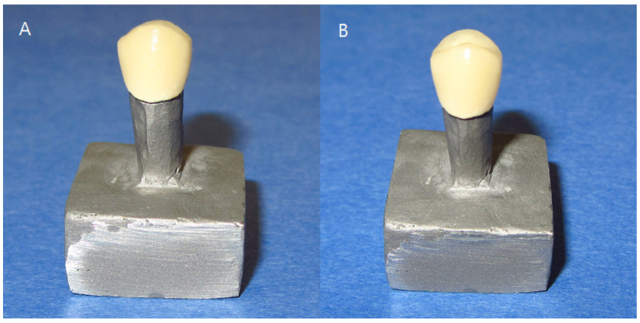

Fig. 5. Specimens after glazing

A – lost-wax group; B – CAD-CAM group.

were placed in a thermocycler (SD Mechatronik, Feldkirchen-Westerham, Germany) and subjected to 3,000 thermal cycles at 5–55°C. Each cycle lasted 60 s, and included 20 s of dwell time and 20 s of transfer time.[29] For cyclic loading, a chewing simulator (CS-4; SD Mechatronik) was used (Fig. 6A). Using deionized water, 100,000 cycles were applied with a load of 100 N and a frequency of 1 Hz, corresponding to 2–3 months of clinical service.[30,31]

Load test

The acrylic die stand was first replaced with the Co-Cr alloy to resist forces. The specimen was then cemented on the metal die with the Temp-Bond™ cement (Kerr, Brea, USA). Next, a load was applied to the specimen by means of a round-end stainless steel bar with a diameter of 5 mm at a crosshead speed of 1 mm/min along the tooth longitudinal axis in a universal testing machine (Santam Co., Tehran, Iran) with a capacity of 200 kgf. The load was applied vertically until the fracture of the specimen occurred (Fig. 6B).[28] The load causing fracture was recorded for each specimen and the mode of failure was determined under a stereomicroscope (SMZ800; Nikon, Tokyo, Japan).

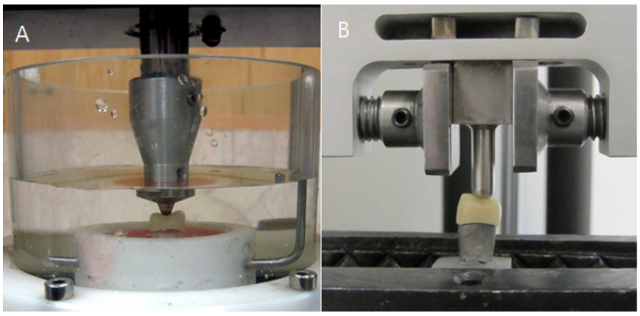

Fig. 6. Simulation of oral conditions and a load test

A – cyclic loading in a CS-4 chewing simulator; B – placement of the specimen in a universal testing machine.

Statistical analysis

The normality of the data was assessed using the Shapiro–Wilk test, and the homogeneity of the data was evaluated using Levene's test. The data was analyzed using IBM SPSS Statistics for Windows, v. 24.0 (IBM Corp., Armonk, USA), and the *t* tests were applied at the significance level of 0.05.

Results

Two specimens were excluded from the CAD-CAM group due to fracture during the study, and 10 specimens in the lost-wax group and 8 specimens in the CAD-CAM group remained in the study. As shown in Table 2, the mean fracture strength was 2,271 ±420 N in the lost-wax group and 2,379 ±531 N in the CAD-CAM group. This difference was not significant ($p > 0.05$). The mode of failure was mixed in all specimens from both groups (Fig. 7).

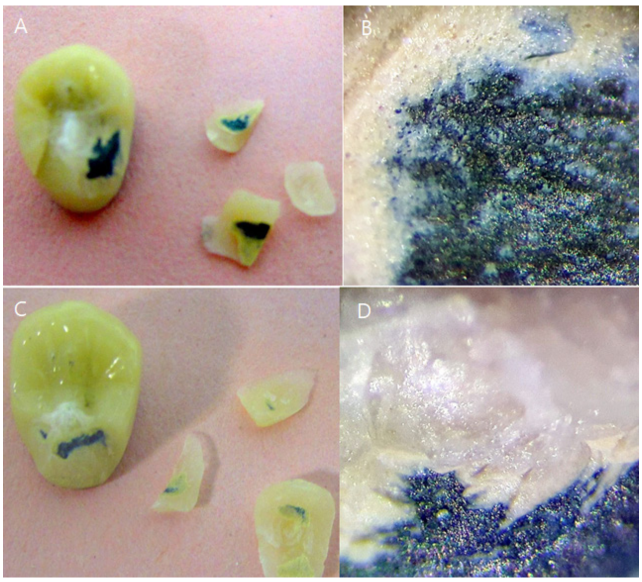

Fig. 7. Fracture surfaces after the load test and the mixed mode of failure

A,B – CAD-CAM group; C,D – lost-wax group.

Table 2. Fracture strength of porcelain in metal-ceramic restorations (MCRs) fabricated with the lost-wax and CAD-CAM techniques, and the mode of failure of the specimens in the 2 groups

Parameter		Lost-wax group *n* = 10	CAD-CAM group *n* = 8
Fracture strength [N] *M* ±*SD*		2,271 ±420	2,379 ±531
Coefficient of variation		18	22
Mode of failure *n*	adhesive	0	0
	cohesive	0	0
	mixed	10	8

M – mean; *SD* – standard deviation.

Discussion

The present study assessed the effect of the lost-wax and CAD-CAM framework fabrication techniques on the fracture strength of porcelain in MCRs. The results showed that the technique of framework fabrication had no significant effect on the fracture strength or the mode of failure of porcelain.

Porcelain chipping/fracture imposes extra costs on patients, and its repair is time-consuming. Both of these factors are clinically important.[25] Thus, adequate metal–ceramic bond strength, metal support for the ceramic material, and/or thickness of the ceramic material are prerequisites in MCRs. Metal–ceramic bond strength depends on many factors, and one of the most influential ones is the metal framework fabrication technique.[15,22]

The composition of the Co-Cr alloy, the porcelain composition, and the difference in the coefficient of thermal expansion (CTE) of the porcelain and the metal are other factors affecting the fracture strength of porcelain.[7,25,32,33] In this study, the CTE of porcelain was $12.9 \pm 0.5 \times 10^{-6}/°C$, the CTE of the Magnum Ceramic Co alloy was $14.1 \times 10^{-6}/°C$ and that of the Ceramill Sintron alloy was $14.5 \times 10^{-6}/°C$; they were all similar. In 2007, Kellerhoff and Fischer measured the fracture strength and thermal shock resistance of MCRs with gold-titanium (Au-Ti) frameworks fabricated with the use of the casting and milling methods.[15] Their results were in contrast to our findings, indicating that the fracture strength of the milling group was significantly lower than that of the casting group. This can be due to the different structure of Au-Ti alloy, since during milling, a soft smear of the Au phase is created on the surface, which serves as a barrier against the diffusion of Ti and prevents the formation of a chemical bond to the ceramic.[15]

No significant difference was noted in the fracture strength of porcelain between the lost-wax and CAD-CAM groups in this study, which may be due to the fact that the specimens had similar oxidation patterns after air abrasion and heat treatment, resulting in similar chemical and mechanical bonding mechanisms. This finding is in agreement with the results of previous studies.[20,21,23,32,33] Previous studies, however, evaluated rectangular or cylindrical specimens, and most of them did not perform thermocycling and/or cyclic loading. In this study, the specimens had the anatomical form of natural teeth, and underwent both thermocycling and cyclic loading to better simulate the clinical setting.[34] The adopted thermocycling protocol in this study simulated 2.5 years of clinical service,[29] while the cyclic loading protocol simulated 2–3 months of clinical service.[31] Also, water has been suggested to play a role in the propagation of small cracks. Thus, we used deionized water instead of artificial saliva, since it has no significant effect on the coefficient of friction between natural teeth.[7,30] Since MCRs have complex geometries, and the effect of the material properties on fracture strength has not been well elucidated, in vitro studies should preferably simulate the clinical setting as much as possible.[15] Two previous studies used specimens with natural tooth anatomy, performed thermocycling and cyclic loading, and reported results similar to our findings.[7,24] Another study evaluated the properties of the metal–ceramic bond in restorations with Co-Cr frameworks fabricated by means of the casting, milling and selective laser melting (SLM) techniques.[22] They found that metal–ceramic bond strength in the casting group was lower than that in the milling and SLM groups. The variability in the results is likely due to not using specimens with tooth-like anatomy, and not performing thermocycling and cyclic loading.[22]

The mode of failure in this study was mixed for all specimens in both groups. However, cohesive failure within the ceramic was dominant in most mixed fractures. Some previous studies reported that the metal framework fabrication technique had no significant effect on the mode of failure.[15,20,21] Similar to our study, Suleiman and von Steyern did not report any adhesive failure and most fractures were mixed; however, in contrast to our findings, some fractures were purely cohesive in their study.[7] These results may indicate the insignificant effect of debonding forces on the mode of failure.

In the load test, only a vertical load is applied to specimens. Thus, it only simulates vertical load application in the oral environment and misses the loads applied from other directions. Accordingly, the findings of this in vitro study, like many others, cannot be acceptably generalized to the clinical setting. Future clinical trials and prospective in vivo studies are required to more validly elucidate this topic.

Conclusions

Our results indicated that the fracture strength of porcelain and its mode of failure are independent of the metal framework fabrication technique (lost-wax or CAD-CAM). Therefore, both metal framework fabrication techniques can be recommended in clinical practice.

Ethics approval and consent to participate

Not applicable.

Data availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Consent for publication

Not applicable.

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References

1. Kocaağaoğlu H, Kılınç Hİ, Albayrak H, Kara M. In vitro evaluation of marginal, axial, and occlusal discrepancies in metal ceramic restorations produced with new technologies. *J Prosthet Dent*. 2016;116(3):368–374. doi:10.1016/j.prosdent.2016.03.013
2. Suarez MJ, Perez C, Pelaez J, Lopez-Suarez C, Gonzalo E. A randomized clinical trial comparing zirconia and metal-ceramic three-unit posterior fixed partial dentures: A 5-year follow-up. *J Prosthodont*. 2019;28(7):750–756. doi:10.1111/jopr.12952
3. Limones A, Molinero-Mourelle P, Azevedo L, Romeo-Rubio M, Correia A, Gómez-Polo M. Zirconia-ceramic versus metal-ceramic posterior multiunit tooth-supported fixed dental prostheses: A systematic review and meta-analysis of randomized controlled trials. *J Am Dent Assoc*. 2020;151(4):230–238 e7. doi:10.1016/j.adaj.2019.12.013
4. Layton D. A critical appraisal of the survival and complication rates of tooth-supported all-ceramic and metal-ceramic fixed dental prostheses: The application of evidence-based dentistry. *Int J Prosthodont*. 2011;24(5):417–427. PMID:21909482.
5. Behr M, Zeman F, Baitinger T, et al. The clinical performance of porcelain-fused-to-metal precious alloy single crowns: Chipping, recurrent caries, periodontitis, and loss of retention. *Int J Prosthodont*. 2014;27(2):153–160. doi:10.11607/ijp.3440
6. Rosenstiel SF, Land MF, Fujimoto J. *Contemporary Fixed Prosthodontics*. 4th ed. St. Louis, MO: Mosby/Elsevier; 2006:752–768.
7. Suleiman SH, von Steyern PV. Fracture strength of porcelain fused to metal crowns made of cast, milled or laser-sintered cobalt-chromium. *Acta Odontol Scand*. 2013;71(5):1280–1289. doi:10.3109/00016357.2012.757650
8. Al Jabbari YS. Physico-mechanical properties and prosthodontic applications of Co-Cr dental alloys: A review of the literature. *J Adv Prosthodont*. 2014;6(2):138–145. doi:10.4047/jap.2014.6.2.138
9. Loch J, Łukaszczyk A, Augustyn-Pieniążek J, Krawiec H. Electrochemical behaviour of Co-Cr and Ni-Cr dental alloys. *Solid State Phenom*. 2015;227:451–454 doi:10.4028/www.scientific.net/ssp.227.451
10. Shamseddine L, Mortada R, Rifai K, Chidiac JJ. Marginal and internal fit of pressed ceramic crowns made from conventional and computer-aided design and computer-aided manufacturing wax patterns: An in vitro comparison. *J Prosthet Dent*. 2016;116(2):242–248. doi:10.1016/j.prosdent.2015.12.005
11. Shell JS, Nielsen JP. Study of the bond between gold alloys and porcelain. *J Dent Res*. 1962;41:1424–1437. doi:10.1177/00220345620410062101
12. Sadeq A, Cai Z, Woody RD, Miller AW. Effects of interfacial variables on ceramic adherence to cast and machined commercially pure titanium. *J Prosthet Dent*. 2003;90(1):10–17. doi:10.1016/s0022-3913(03)00263-4
13. Vojdani M, Torabi K, Farjood E, Khaledi A. Comparison the marginal and internal fit of metal copings cast from wax patterns fabricated by CAD/CAM and conventional wax up techniques. *J Dent (Shiraz)*. 2013;14(3):118–129. PMID:24724133. PMCID:PMC3927676.

14. Friedlander LD, Munoz CA, Goodacre CJ, Doyle MG, Moore BK. The effect of tooth preparation design on the breaking strength of Dicor crowns: Part 1. *Int J Prosthodont*. 1990;3(2):159–168. PMID:2133383.
15. Kellerhoff RK, Fischer J. In vitro fracture strength and thermal shock resistance of metal-ceramic crowns with cast and machined AuTi frameworks. *J Prosthet Dent*. 2007;97(4):209–215. doi:10.1016/j.prosdent.2007.02.007
16. Hendi A, Falahchai M, Maleki D, Maleki D. Composite preheating. *Journal of Dentomaxillofacial Radiology, Pathology and Surgery*. 2019;8(1):37–40. https://3dj.gums.ac.ir/article-1-464-en.pdf. Accessed July 1, 2021.
17. Padrós R, Punset M, Molmeneu M, et al. Mechanical properties of CoCr dental-prosthesis restorations made by three manufacturing processes. Influence of the microstructure and topography. *Metals*. 2020;10(6):788. doi:10.3390/met10060788
18. Barro Ó, Arias-González F, Lusquiños F, et al. Effect of four manufacturing techniques (casting, laser directed energy deposition, milling and selective laser melting) on microstructural, mechanical and electrochemical properties of Co-Cr dental alloys, before and after PFM firing process. *Metals*. 2020;10(10):1291. doi:10.3390/met10101291
19. Katsoulis J, Mericske-Stern R, Rotkina L, Zbären C, Enkling N, Blatz MB. Precision of fit of implant-supported screw-retained 10-unit computer-aided-designed and computer-aided-manufactured frameworks made from zirconium dioxide and titanium: An in vitro study. *Clin Oral Implants Res*. 2014;25(2):165–174. doi:10.1111/clr.12039
20. Li J, Chen C, Liao J, et al. Bond strengths of porcelain to cobalt-chromium alloys made by casting, milling, and selective laser melting. *J Prosthet Dent*. 2017;118(1):69–75. doi:10.1016/j.prosdent.2016.11.001
21. Serra-Prat J, Cano-Batalla J, Cabratosa-Termes J, Figueras-Àlvarez O. Adhesion of dental porcelain to cast, milled, and laser-sintered cobalt-chromium alloys: Shear bond strength and sensitivity to thermocycling. *J Prosthet Dent*. 2014;112(3):600–605. doi:10.1016/j.prosdent.2014.01.004
22. Wang H, Feng Q, Li N, Xu S. Evaluation of metal-ceramic bond characteristics of three dental Co-Cr alloys prepared with different fabrication techniques. *J Prosthet Dent*. 2016;116(6):916–923. doi:10.1016/j.prosdent.2016.06.002
23. Kaleli N, Saraç D. Comparison of porcelain bond strength of different metal frameworks prepared by using conventional and recently introduced fabrication methods. *J Prosthet Dent*. 2017;118(1):76–82. doi:10.1016/j.prosdent.2016.12.002
24. Krug KP, Knauber AW, Nothdurft FP. Fracture behavior of metal-ceramic fixed dental prostheses with frameworks from cast or a newly developed sintered cobalt-chromium alloy. *Clin Oral Investig*. 2015;19(2):401–411. doi:10.1007/s00784-014-1233-2
25. Hong JT, Shin SY. A comparative study on the bond strength of porcelain to the millingable Pd-Ag alloy. *J Adv Prosthodont*. 2014;6(5):372–378. doi:10.4047/jap.2014.6.5.372
26. Brunner KC, Özcan M. Load bearing capacity and Weibull characteristics of inlay-retained resin-bonded fixed dental prosthesis made of all-ceramic, fiber-reinforced composite and metal-ceramic after cyclic loading. *J Mech Behav Biomed Mater*. 2020;109:103855. doi:10.1016/j.jmbbm.2020.103855
27. Michalakis KX, Stratos A, Hirayama H, Kang K, Touloumi F, Oishi Y. Fracture resistance of metal ceramic restorations with two different margin designs after exposure to masticatory simulation. *J Prosthet Dent*. 2009;102(3):172–178. doi:10.1016/S0022-3913(09)60141-4
28. Urapepon S, Taenguthai P. The effect of zirconia framework design on the failure of all-ceramic crown under static loading. *J Adv Prosthodont*. 2015;7(2):146–150. doi:10.4047/jap.2015.7.2.146
29. Henriques B, Gonçalves S, Soares D, Silva FS. Shear bond strength comparison between conventional porcelain fused to metal and new functionally graded dental restorations after thermal-mechanical cycling. *J Mech Behav Biomed Mater*. 2012;13:194–205. doi:10.1016/j.jmbbm.2012.06.002
30. DeLong R, Douglas WH. An artificial oral environment for testing dental materials. *IEEE Trans Biomed Eng*. 1991;38(4):339–345. doi:10.1109/10.133228
31. Alvarez-Arenal A, Gonzalez-Gonzalez I, deLlanos-Lanchares H, Brizuela-Velasco A, Pinés-Hueso J, Ellakuria-Echebarria J. Retention strength after compressive cyclic loading of five luting agents used in implant-supported prostheses. *Biomed Res Int*. 2016;2016:2107027. doi:10.1155/2016/2107027
32. Stawarczyk B, Eichberger M, Hoffmann R, et al. A novel CAD/CAM base metal compared to conventional CoCrMo alloys: An in-vitro study of the long-term metal-ceramic bond strength. *Oral Health Dent Manag*. 2014;13(2):446–452. PMID:24984663.
33. Choi YJ, Koak JY, Heo SJ, Kim SK, Ahn JS, Park DS. Comparison of the mechanical properties and microstructures of fractured surface for Co-Cr alloy fabricated by conventional cast, 3-D printing laser-sintered and CAD/CAM milled techniques. *J Korean Acad Prosthodont*. 2014;52(2):67–73. doi:10.4047/jkap.2014.52.2.67.
34. Lopez-Suarez C, Tobar C, Sola-Ruiz MF, Pelaez J, Suarez MJ. Effect of thermomechanical and static loading on the load to fracture of metal-ceramic, monolithic, and veneered zirconia posterior fixed partial dentures. *J Prosthodont*. 2019;28(2):171–178. doi:10.1111/jopr.13008