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Rodrigo Ottoni

OTIMIZAÇÃO DO DESEMPENHO DE COROAS CERÂMICAS MONOLÍTICAS UTILIZANDO DELINEAMENTO DE EXPERIMENTOS

Passo Fundo

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OTIMIZAÇÃO DO DESEMPENHO DE COROAS CERÂMICAS MONOLÍTICAS UTILIZANDO DELINEAMENTO DE EXPERIMENTOS

Tese apresentada ao Programa de Pós-Graduação em Odontologia da Faculdade de Odontologia da UPF, para obtenção do título de Doutor em Odontologia – Área de Concentração em Clínica Odontológica, sob orientação da profa. Dra. Márcia Borba e co-orientação do prof. Dr. Pedro Henrique Corazza.

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RESUMO[1]

O objetivo dessa tese foi avaliar a influência do tipo de processamento da cerâmica, do preparo do pilar e método de escaneamento na adaptação e comportamento mecânico de coroas monolíticas de vitrocerâmica à base de dissilicato de lítio (LD), utilizando o método estatístico de delineamento de experimentos (DOE). O estudo foi dividido em dois artigos científicos. O primeiro artigo buscou definir a combinação ideal de fatores para coroas totais de cerâmica. Quarenta preparos de pilar, chanfro (C) e ombro arredondado (S), foram produzidos com um material análogo à dentina e digitalizados através de escaneamento extraoral (E) ou intraoral (I). As imagens capturadas foram processadas usando o software CAD para desenhar um pré-molar. Blocos de LD foram usinados em sistema CAD/CAM (Cad). Para a técnica de prensagem (Press), as coroas foram inicialmente impressas em 3D usando um material polimérico e o protocolo de prensagem a quente foi realizado. DOE foi usado para planejar os grupos experimentais. A adaptação foi medida usando a técnica da réplica. As coroas foram cimentadas com cimento resinoso nos

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respetivos pilares e uma carga compressiva foi aplicada usando uma máquina de teste universal até a fratura. A análise fractográfica foi realizada. ANOVA e análises estatísticas de regressão foram usadas para investigar os efeitos significativos para cada variável dependente, e a melhor combinação de fatores foi calculada. O tipo de preparo e o método de escaneamento não influenciaram a adaptação e a carga de fratura das coroas. Cad resultou em maior espessura de fenda nas áreas oclusal, ângulo axial e marginal e menor espessura na área axial; não houve efeito do método de processamento na carga de fratura. A combinação ideal de fatores para coroas totalmente de cerâmica é o preparo tipo chanfro, escaneamento extraoral e método de fabricação Press (combinado com impressão 3D). O segundo artigo avaliou a adaptação e comportamento à fadiga de coroas monolíticas de LD produzidas por Cad e Press (combinadas com impressão 3D). Trinta preparos do tipo chanfro foram produzidos com um material análogo à dentina, digitalizados com escâner extraoral e as coroas foram processadas como descrito no artigo 1. As coroas foram escaneadas usando micro-tomografia computadorizada e as imagens foram processadas pra avaliar a adaptação. O teste de fadiga foi realizado em máquinas MTS (2 Hz, água destilada 37ºC) utilizando um pistão anatômico de compósito, seguindo o método step-stress. As falhas foram detectadas com um sistema acústico e confirmadas por transiluminação. *Cumulative damage-Weibull*

distribution (95% CL) foi usada para analisar os dados de fadiga. Os dados de adaptação foram analisados usando ANOVA de dois fatores e teste post hoc de Tukey ($\alpha = 0,05$). Cad resultou em maior espessura de fenda na oclusal e menor espessura no ângulo axial e área axial. A probabilidade de falha em fadiga foi semelhante para Cad e Press. As trincas do tipo radial foram encontradas com maior frequência. As coroas LD produzidas usando a combinação de impressão 3D/Press apresentaram uma espessura de fenda mais homogênea do que as coroas produzidas com Cad. No entanto, o comportamento à fadiga foi semelhante para ambas as estratégias para produzir coroas monolíticas de LD.

Palavras-chave: Adaptação; Delineamento de Experimentos; Fadiga; Falha de Restauração Dentária; Prótese; Otimização.

ABSTRACT[2]

The objective of this thesis is to evaluate the influence of the type of ceramic processing, abutment preparation and scanning method in the adaptation and mechanical behavior of lithium disilicate glass-ceramic (LD) monolithic crowns, using the statistical method of design of experiments (DOE). The study was divided into two scientific articles. The first article aimed to define the ideal combination of factors for all-ceramic crowns. Forty abutments preparations, chamfer (C) and rounded shoulder (S), were produced with a dentin analog material and digitized through extraoral (E) or intraoral (I) scanning. The captured images were processed using CAD software to design a premolar. LD glass ceramic blocks were milled in a CAD/CAM system (Cad). For the pressing technique (Press), the crowns were initially 3D printed using a polymeric material and the heat-pressing protocol was performed. DOE was used to plan the experimental groups. Adaptation was measured using the replica technique. The crowns were cemented with resin cement on the respective abutment and a

[2] Optimization of monolithic ceramic crowns performance using design of experiments.

compressive load was applied using a universal testing machine until fracture. Fractographic analysis was performed. ANOVA and statistical regression analysis were used to investigate the significant effects for each dependent variable, and the best combination of factors was calculated. The type of preparation and the scanning method did not influence the adaptation and fracture load of the crowns. Cad resulted in greater gap thickness in the occlusal area, axial and marginal angle and smaller thickness in the axial area; there was no effect of the ceramic processing method on the fracture load. The ideal combination of factors for all-ceramic crowns is chamfer preparation, extraoral scanning and Press technique (combined with 3D printing). The second article evaluated the adaptation and fatigue behavior of LD monolithic crowns produced by Cad and Press (combined with 3D printing) Thirty chamfer preparations were produced with a dentin analog material and digitized with an extraoral scanner; crowns were processed as described in article 1. The crowns were scanned using a micro-CT and images were processed to evaluate the adaptation. The fatigue test was performed on MTS machines (2 Hz, 37^{o}C distilled water) using a compositeanatomical piston, following the step-stress method. The failures were detected with an acoustic system and confirmed by transillumination. The cumulative damage-Weibull distribution (95% CL) was used to analyze the fatigue data. Adaptation data were analyzed using two-way

ANOVA and Tukey's post hoc test ($\alpha = 0.05$). Cad resulted in greater gap thickness in the occlusal and smaller thickness in the axial angle and axial area. The fatigue failure probability was similar for Cad and Press. Radial cracks were the most frequent failure mode for both groups. LD crowns produced using the 3D printing/Press combination showed a more homogeneous gap thickness than crowns produced with Cad. However, the fatigue behavior was similar for both strategies used to produce monolithic LD crowns.

Keywords: Adaptation; Design of Experiments; Dental Restoration Failure; Fatigue; Prosthesis; Optimization.

INTRODUÇÃO

O desempenho clínico de próteses fixas monolíticas é influenciado por diversos fatores, entre eles o tipo de material restaurador, a qualidade do preparo e as etapas de processamento. Esses fatores podem afetar tanto a adaptação como o comportamento mecânico da restauração. A adaptação marginal pode estar diretamente ligada a degradação do agente de cimentação e o surgimento de cáries e doença periodontal, devido à impacção alimentar em casos de fendas maiores (HEINTZE, 2007; SARRET, 2007). A adaptação interna também pode afetar o comportamento mecânico das restaurações protéticas, pois os agentes de cimentação apresentam baixo módulo de elasticidade e possuem maior contração de polimerização quando usados em maior espessura, podendo resultar em áreas de concentração de tensões na interface de cimentação que podem levar a falhas precoces das restaurações (BORBA *et al*., 2011; KUNII *et al.*, 2007; MAY *et al.,* 2012).

O preparo do pilar apresenta diversas configurações dependendo do tipo de dente e restauração a ser executada. Pode-se variar a forma do término (chanfro e ombro) ou sua angulação (ombro executado em graus diferentes), a angulação das paredes axiais e o ângulo de convergência oclusal (SOUZA *et al.,* 2012; CORAZZA *et al*., 2013; TIU *et al.,* 2015). Alguns estudos vem mostrando que o tipo de término (chanfro ou ombro arredondado) influencia diretamente na adaptação marginal dessas restaurações, com forte relação com a capacidade de cópia dessa região (SOUZA *et al.,* 2012; TIU *et al.,* 2015).

O desempenho das restaurações protéticas também está relacionado com o processamento, desde a etapa de captação das imagens do preparo até as etapas de confecção da restauração final pelo sistema CAD/CAM (c*omputer aided design/computer aided manufacturing*). A técnica de captação das imagens pode ser realizada diretamente na boca do paciente, por meio de câmeras intra-orais, ou através da digitalização do modelo do paciente (escâneres extra-orais). No escaneamento extra-oral podem haver imprecisões devido a mudanças dimensionais nos materiais de impressão e no gesso que influenciam na adaptação interna e marginal das restaurações cerâmicas (CHRISTENSEN, 2008). Já nos escâneres intra-orais, a precisão pode ser afetada por fatores como o movimento do paciente durante a aquisição da imagem, o reflexo da luz da superfície do dente, da saliva ou da umidade (ANADIOTI *et al.,* 2015; JEONG *et al.,* 2016).

A vitrocerâmica à base de dissilicato de lítio (LD) é composta por cristais alongados de dissilicato de lítio ($Li2Si2O5$) (60 a 70% em volume) dispersos aleatoriamente em uma matriz vítrea de forma interlaçada (BELLI *et al*., 2017). Devido à translucidez favorável, a variedade de cores e a alta resistência do material, essa cerâmica é indicada para *inlays, onlays*, coroas unitárias e facetas laminadas, e para infraestrutura de próteses fixas de três elementos anteriores até segundo pré-molar (MORES *et al*., 2017). Para essa cerâmica existem dois métodos de fabricação, a técnica CAD/CAM e a técnica da injeção (prensagem a quente). Atualmente também é possível realizar a impressão 3D da restauração em polímero, posterior inclusão do “enceramento” em um molde refratário, queima da cera/polímero em forno convencional e injeção da cerâmica a uma temperatura de 920º C. Estudos mostraram que não existe diferença na resistência inicial da DL produzida por CAD/CAM ou por injeção, mas há uma maior degradação mecânica para as restaurações de DL produzidas por CAD/CAM (BELLI *et al.,* 2014).

O planejamento e execução de pesquisas laboratoriais pode ser muito demorado e de custo muito elevado para os pesquisadores se considerarmos a grande quantidade de fatores que influenciam o desempenho clínico de restaurações protéticas. Isso pode restringir o número de fatores investigados e testes realizados. Assim, para otimizar as pesquisas pode-se utilizar um conjunto de técnicas estatísticas denominado Delineamento de Experimentos (DOE). O primeiro passo é identificar as variáveis independentes ou fatores que afetam o produto ou o processo e depois estudar seus efeitos em uma variável ou resposta dependente. Para desenvolver os melhores produtos e processos possíveis da maneira mais econômica, é necessário planejar cuidadosamente o processo de teste para que todos os fatores relevantes e potenciais interações de fatores sejam considerados sem desperdiçar tempo, esforço ou dinheiro. O DOE pode ser utilizado em todas as áreas das ciências naturais e sociais para desenvolver estratégias de experimentação que maximizem a aprendizagem usando um mínimo de recursos. O experimentos geralmente são realizados em cinco etapas: planejamento, triagem, otimização, teste de robustez e verificação (Weibull++/ALTA 11 User's Guide).

A etapa de planejamento é importante para definir as variáveis independentes e dependentes de maior interesse, resultando em economia de tempo e recursos. O objetivo da etapa de triagem é determinar quais variáveis independentes são importantes o suficiente para examinar em maior profundidade. A etapa de otimização inicia depois que os fatores importantes foram identificados, o objetivo é determinar as configurações desses fatores que, juntos, produzirão o resultado desejado. O pesquisador deverá considerar o objetivo definido para cada resposta e, nos casos em que as respostas múltiplas são medidas, talvez seja necessário considerar a importância relativa de cada resposta ao determinar as melhores soluções. No DOE, depois de analisar dados de um experimento com pelo menos dois fatores, uma programação de otimização pode ser usada para otimizar as configurações do fator (Weibull++/ALTA 11 User's Guide).

Embora o ambiente experimental possa ser cuidadosamente controlado, é provável que existam fatores que afetam o produto ou processo no ambiente de aplicação e estão fora do controle do pesquisador. O objetivo do teste de robustez é identificar esses fatores e garantir que o produto ou processo seja insensível ou robusto. Na fase de verificação, o pesquisador confirma os resultados obtidos das fases anteriores realizando alguns experimentos de acompanhamento para verificar se os valores de resposta observados estão próximos dos valores previstos. O objetivo é validar as melhores configurações que foram determinadas, certificando-se de que o produto ou processo funciona como desejado e que todos os objetivos sejam atendidos (Weibull++/ALTA 11 User's Guide).

PROPOSIÇÃO

Objetivo Geral

Este estudo tem como objetivo geral avaliar a influência do tipo de processamento da cerâmica, do preparo do pilar e método de escaneamento na adaptação e comportamento mecânico de coroas monolíticas à base de dissilicato de lítio, utilizando o método estatístico de delineamento de experimentos (DOE).

Objetivos Específicos

Os objetivos específicos são:

1) avaliar o efeito dos fatores em estudo na adaptação das coroas, através da técnica da réplica e avaliação com micro-tomografia computadorizada;
2) avaliar o efeito dos fatores em estudo no comportamento mecânico das coroas, utilizando os testes de carga de fratura e fadiga cíclica;
3) definir a combinação ideal de fatores (melhor adaptação e desempenho mecânico) para a produção de coroas cerâmicas e otimizar o estudo através do método DOE.

ARTIGO I

Design optimization of all-ceramic crowns

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Abstract

Objectives: to define the optimal combination of factors (abutment finish line, scanning method and ceramic processing) to achieve the best performance (adaptation and fracture load) of all-ceramic crowns.

Methods: Abutment preparations, chamfer (C) and rounded shoulder (S), were produced with a dentin analogue material and scanned with extraoral (E) or intraoral (I) scanners. Captured images were processed using CAD software to design a premolar. Blocks of lithium disilicate glass-ceramic (LD) were milled using CAD/CAM system (Cad). For the press technique (Pre), crowns were first 3D-printed using a polymeric material and the heat-pressing protocol was performed. Design of experiments was used to plan the experimental groups (n =10): CadCE, CadSI, PreCE, PreSI. Adaptation was measured using the replica technique. Crowns were adhesively cemented to the abutments and loaded to fracture using a universal testing machine. Fractographic analysis was performed. ANOVA and regression statistical analyses were used to investigate the significant effects for each dependent variable, and the best combination of factors was calculated.

Results: The abutment finish line and scanning method did not influence the crown's adaptation and fracture load. CAD/CAM resulted in larger gap thickness in the occlusal, axial angle and marginal areas and smaller gap thickness in the axial area ($p < 0.001$); whereas there was no effect of the processing method on the fracture load. The optimum design parameters achieved 100% of the desired fracture load (N) and 40% of the desired adaptation (μm).

Significance: The optimum combination of factors for the all ceramic crowns is chamfer abutment preparation, extraoral scanning and the press technique (combined with 3Dprintting).
Keywords: 3D Printing. CAD/CAM. Ceramics. Dental Prosthesis. Optimization. Resin Cement.

1. INTRODUCTION

Design-related factors can affect the clinical performance of all-ceramic fixed dental prostheses. The type of abutment preparation and the processing steps involved in the production of ceramic restorations may influence its adaptation and mechanical behavior [1-8], resulting in biological and technical complications [9, 10]. Large marginal gaps could lead to the degradation of the luting agent and increase the susceptibility of caries and periodontal disease, due to food impaction [11, 12]. The quality of the internal adaptation may also affect the mechanical behavior of ceramic restorations. Resin cements have a low elastic modulus and show a higher polymerization shrinkage when used in greater thickness, which induces higher tensile stresses at the cementation interface that may lead to early restoration failures [13].

The CAD/CAM system is widely used to produce ceramic restorations, and involves three steps: data acquisition, computer-aided design (CAD) and manufacturing (CAM). Images can be obtained directly from the patient's mouth, using intraoral scanners, or indirectly, through the digitalization of the plaster model (extraoral scanners) [5, 14]. The quality of images obtained using extraoral scanners are susceptible to inaccuracies due to dimensional changes in printing and plaster materials [15]. Yet, when intraoral scanners are used, the accuracy may be affected by factors such as patient movement during image acquisition, reflection of tooth surface and saliva [14, 16]. Therefore, there is no consensus in the literature on the best scanning technique to capture images from a prosthetic preparation [5, 14, 16].

In addition, the type abutment finish line (chamfer or rounded shoulder) could also influence the quality of copy of this region by the impression materials and the scanning devices [2, 4, 17]. Studies found smaller marginal gaps for ceramic restorations produced by the conventional layering technique when abutments with chamfer finish lines were used [18, 19]. On the contrary, rounded shoulder finish lines resulted in superior marginal fit for ceramic restorations produced by CAD/CAM; probably due to the challenges of milling the concave and convex areas in the tilted surfaces of the chamfer finish line [20].

Other manufacturing methods are also available to produce ceramic restorations. Lithium disilicate glass-ceramic (LD) restorations can be either processed by CAD/CAM or by the press technique [21-23]. Studies have shown that there is no difference in the LD initial strength produced using the different methods, but the strength degradation is greater for specimens produced by CAD/CAM (53.4%) than for the press technique (29.6%) [23]. For monolithic crowns, lithium disilicate glass-ceramic (LD) is widely used due to its good balance between mechanical and optical properties [23-26]. LD is composed of needle-shaped lithium disilicate ($Li_2Si_2O_5$) crystals randomly orientated in an interlocking glass matrix [27].

More recently, 3D-printting was introduced in Dentistry and a modification of the press technique was proposed. Data acquisition and processing follow the same steps of the conventional CAD/CAM system; but the subtractive technique is replaced by the additive one [28]. The STL data file designed using the CAD software is converted using a 3D-printer software into a STL file/3D structure and virtually dissected into several layers. After that, the restoration is designed though a layer-by-layer fabrication process using a polymeric material [29, 30]. Finally, the 3D-printed polymer restoration is processed using the press technique to produce the final LD restoration.

Overall, clinical studies show high survival rates for LD crowns supported by tooth (>96.5% in 10.4 years) [9, 31-33]. Belli et al. [32] estimated a 10% failure probability for LD crowns after a 20 years follow-up. Nevertheless, there is a high variability in the clinical findings as the variables involved in the restorations design are difficult to control; and long-term follow-ups are scare. In addition, laboratory studies on these design-related factors could be limited by the cost and time necessary to plan and execute the research. Thus, to optimize the research, a set of statistical techniques called Design of Experiments (DOE) was proposed. In order to develop the best possible products and processes in the most cost-effective manner, careful planning of the testing process is necessary so that the relevant factors are considered without wasting time and resources [34, 35]. Experiments are usually performed in five steps: planning, screening, optimization, robustness testing and verification [35].

Therefore, the objective of this study was to evaluate the influence of design-related factors on the adaptation and mechanical behavior of all-ceramic LD monolithic crowns. The study hypothesis is that the finish line, scanning method and type of ceramic processing have no effect on the gap thickness and load to fracture of the ceramic crowns. DOE was used to plan, execute and analyze data in order to predict the optimal design (combination of factors) to achieve the best performance (smallest gap thickness and highest fracture load) of the all-ceramic crowns.

2. MATERIALS AND METHODS

Three factors were investigated in this study, each one with two levels: (1) finish line: C – chamfer or S – rounded shoulder; (2) scanning method: I - intraoral or E - extraoral scanner; (3)

ceramic processing method: Cad – CAD/CAM or Press- 3D-printing followed by the press technique. Monolithic all-ceramic crowns with the design of an upper second premolar were produced using lithium disilicate-based glass-ceramic (LD) according to the independent variables described above. Two dependent variables were evaluated: (1) gap thickness (adaptation) and (2) fracture load.

2.1 Design of Experiments

A software for design of experiments (DOE) (Weibull++/ALTA PRO, HBM Prenscia Inc., Tucson, AZ, USA) was used to estimate the experimental groups for adaptation and fracture load evaluations. Taguchi's Orthogonal Arrays model, which is a fractional design, was chosen with the objective of investigating the main effects with reduced number of groups and sample size. Parameters used were: 2 responses (adaptation and fracture load), 3 factors (qualitative), 2 levels each and 10 replicates. A total of four groups and 40 specimens were estimated for the experiment (Taguchi design type = L4(2^3)), according to Table 1. The same experimental groups and specimens were evaluated for adaptation and load to fracture.

Table 1. Experimental groups and sample size according to DOE planning.

Group	Ceramic Processing	Finish Line	Scanning Method	n
CadCI	CAD/CAM	Chamfer	Intraoral	10
CadSE	CAD/CAM	Rounded Shoulder	Extraoral	10
PreCE	Press	Chamfer	Extraoral	10
PreSI	Press	Rounded Shoulder	Intraoral	10

2.2 Specimen Preparation

2.2.1 Abutment

Two types of abutment preparation were designed and produced by milling a dentin analogue material (Fiber-reinforced epoxy resin, NEMA grade G10, International Paper, Hampton, USA)) [36, 37]. First, two digital models were designed using a CNC software (Romi GL240, Romi Industries S.A., Santa Barbara d'Oeste, SP, Brazil). All preparations had dimensions of 6 mm in height, 8 mm in diameter and 12º of total occlusal convergence (TOC) with all transitions between the axial and occlusal walls round, smooth and homogeneous. The difference between the preparations was the finish line. The chamfer finish line (C) has a radius of 1.2 mm between the cervical area and axial wall. The rounded shoulder (S) has a cervical horizontal base (0.6 mm) and a radius of 0.4 mm between the cervical base and the axial wall [2, 3]. The G10 abutments were milled using a mechanic lathe (Romi GL240, Romi Industries S.A., Santa Barbara d'Oeste, SP, Brazil).

Twenty abutments were produced for each finish line. The abutments were stored in distilled water at 37º C for 15 days to allow hygroscopic expansion of the material and to release the residual stresses.

2.2.2 Scanning

Two types of scanners were used to scan the abutments, an extraoral (InEos X5, Sirona Dental Systems GmbH, Salzburg, Germany) and an intraoral (CEREC Omnicam, Sirona Dental Systems GmbH, Salzburg, Germany). Before the scanning procedure, the abutment was inserted in a master model with adjacent teeth to simulate the clinical condition.

For the extraoral scanning, simultaneous impression technique of the abutments were obtained using polyvinysiloxane (Scan Putty, Scan Light, Yller Biomaterials S/A, Pelotas, Brazil). Then, models were produced using a special plaster for CAD/CAM (Vita In-Ceram Special Plaster, Vita Zahnfabrik, Germany) and were placed in the extraoral scanner to capture the images. Twenty models were produced and extraorally scanned, 10 of each finish margin preparation.

Intraoral scanning was performed using the original abutments. Video scanning initiated at the center of the preparation with the camera at a 45-degree angle and continuous data were obtained by moving it to the mesial, lingual, distal and buccal surfaces. Twenty abutments were intraorally scanned, 10 of each finish line preparation.

2.2.3 Ceramic Processing

Images obtained from both scanners were processed using CEREC Connect v4.3 software (Dentsply Sirona Deutschland Gmbh, Germany). All crowns followed the same design of an upper second premolar, using a 90 µm digital cement spacer. For the CAD/CAM processing groups, crowns were milled from precrystallized LD blocks (e.max CAD, Ivoclar Vivadent NA, Amherst, NY, USA). After milling, crowns were crystallized in a specific furnace (Programat P310, Ivoclar Vivadent NA, Amherst, NY, USA).

For the press groups, crowns were first 3D-printed using a polymeric material (VarseoWax CAD/Cast, BEGO, Bremen, Germany) in a 3D printer (Varseo, BEGO, Bremen, Germany). The 3D printed polymer crowns were included in a cast investment (Bellavest SH, BEGO, Bremen, Germany) and taken to a ring furnace (Knebel FAMS, Kota, Cotia, SP, Brazil) at 900 °C for 1 h to volatilize the polymer. Then, DL ingots (e.max PRESS, Ivoclar Vivadent NA, Amherst, NY, USA) were pressed in a special furnace (Programat EP5000, Ivoclar Vivadent NA, Amherst, NY, USA) at a pre-programmed cycle of 18 min at the maximum temperature of 910°C. The crowns were removed from the investment interior, polished with silicone burs and cleaned in an ultrasonic bath for 5 min with distilled water.

2.3 Adaptation

Prior to cementation, internal and marginal adaptation of all crowns were evaluated using the replica technique [6]. For this technique, a low viscosity polyvinyl siloxane impression material (Scan Ultra Light, Yller Biomaterials S/A, Pelotas, Brazil) was inserted into the inner portion of the crown using mixing tips attached to a device. The crown filled with impression material was placed over the respective abutment under digital pressure. Then, a static load of 7.5 N was applied to the occlusal surface of the crown until complete polymerization of the impression material (6 min).

After removing the crown with the impression material simulating the cement layer, the excess of polyvinyl siloxane was removed from the margins with a surgical blade (n 15, Solidor, Lamedid, Osasco, Brazil). The space occupied by the abutment was filled with low viscosity polyvinyl siloxane (Scan Light, Yller Biomateriais S/A, Pelotas, Brazil) of a different color (yellow) to obtain a consistent structure that could be removed from the interior of the crowns.

An extra layer of polyvinyl siloxane (Scan Light, Yller Biomateriais S/A, Pelotas, Brazil) was added to the external surface of the cement analog layer to avoid damaging the replica during the cutting process. A surgical blade was used to cut the replica, in the occlusal-gingival direction, into two equal parts. Images were obtained using a DSRL camera and were evaluated with an image processing software (ImageJ Launcher, National Institutes for Health, Bethesda, USA). The cement gap thickness was measured in five predefined regions [1, 6]: 1) marginal; 2) axial angle; 3) axial; 4) occlusal angle; 5) occlusal. One calibrated operator performed all the measurements.

2.4 Cementation

The cementation surfaces of the crown and the abutment were etched with 10% hydrofluoric acid (CONDAC Porcelana, FGM, Joinvile, SC, Brazil) for 20 and 60 seconds, respectively, and rinsed with water for 60 seconds. All crowns and abutments were cleaned in an ultrasonic bath with distilled water, dried and a silane agent (Monobond N, Ivoclar Vivadent NA, Amherst, NY, USA) was applied and let evaporate for 60 seconds.

Self-adhesive resin cement (Multilink N, Ivoclar Vivadent NA, Amherst, NY, USA) was inserted into the interior of the crown, which was seated with manual pressure over the respective abutment. Then, a constant load of 7.5 N was applied in the occlusal surface of the crown for 5 min. The excess cement was removed, a glycerin gel was applied to the adhesive interface, and each surface was light activated (RADIICAL SDI, Victoria, Australia; 1200 mW/cm^2) for 20 seconds (total time: 100 seconds). The cemented crowns were stored in distilled water at 37°C for 7 days.

2.5 Fracture load test and fractography

A gradual compressive load (0.5 mm/min) was applied to the center of the occlusal surface of the crowns until fracture using a spherical stainless steel piston (6 mm in diameter), in a universal testing machine (Instron 2300, Series 23, Sao Jose dos Pinhais, PR, Brazil). A silicone strip was placed between the occlusal surface of the crowns and the piston to allow a more uniform stress distribution during the test. The test was performed in 37ºC distilled water. The load at fracture (N) was recorded.

The fracture surfaces of twenty-five specimens tested in the fracture load test were sputter-coated with gold-palladium and analyzed under optical microscope (Leica MZ12s, Leica Microsystems GmbH, Wetzlar, Germany). A more detailed analysis of the fracture surface was made using a scanning electron microscope (SEM, Zeiss Supra40, Carl Zeiss AG, Oberkochen, Germany) to identify the characteristics of the fracture surface and failure origin [38]. Failures were classified according to the critical crack location: ceramic intaglio surface (radial crack) and occlusal surface.

2.7 Statistical analysis and optimization

The mean gap thickness and fracture load of each crown were analyzed using ANOVA to define the most important factors for each dependent variable ($\alpha = 0.01$), and a regression test was used to define the importance of each factor. For the adaptation, ANOVA statistics was also used to analyze the effect of each factor on each measurement region separately ($\alpha = 0.01$).

The best combination of factors to achieve an optimal adaptation (smaller gap thickness: <200 mm) and fracture load (higher fracture load: >1000 N) was estimated using a statistical software (ReliaSoft Weibull++/ALTA PRO). The optimization details are presented in Table 2. The global desirability (D) for each combination of factors was calculated as the harmonic mean of the desirability scores of the two dependent variables (D_L - fracture load and D_A - adaptation), meaning that $D = \sqrt{D_L} \times \sqrt{D_A}$.

Table 2. Optimization details used to estimate the best combination of factors to achieve minimum gap thickness and maximum fracture load.

Dependent Variable	Goal	Lower limit	Target	Upper Limit	Weight	Desirability Equation
Fracture load (N)	Maximize	1000	1300		1	$D_L = \frac{Load - 1000}{1300 - 1000}$
Adaptation (µm)	Minimize		100	200	1	$D_A = \frac{200 - Gap}{200 - 100}$

3. RESULTS

Table 3 shows the gap thickness (µm) in the different measurement regions for the experimental groups. There was no effect of the scanning method and finish line for the gap thickness in the different regions. The processing method was significant for the occlusal, axial, axial angle and marginal gap ($p \leq 0.01$). CAD/CAM resulted in larger gap thickness in the occlusal, axial angle and marginal regions and smaller gap thickness in the axial area.

To define the optimal design, the mean gap thickness (considering all mesurement regions) and the fracture load were considered (Table 3). When the mean gap thickness and fracture load were analyzed separately, there was a significant effect of the processing method for the mean gap thickness ($p \leq 0.01$), but none of the factors studied affected the fracture load.

Table 3. Gap thickness and fracture load results for the experimental groups.

Group	Gap thickness (μm) – mean and standard deviation (SD)						Fracture load in N (SD)
	Marginal	Axial angle	Axial	Occlusal angle	Occlusal	Mean (all regions)	
CadCI	388.0 (237.0) a	288.4 (154.0) a	74.1 (21.8) b	198.9 (83.5) a	464.6 (186.0) a	282.8 (123.2) a	1119.4 (179.5) a
CadSE	388.6 (165.8) a	341.1 (115.6) a	61.1 (19.7) b	229.9 (53.1) a	517.9 (157.9) a	307.7 (93.9) a	1172.5 (125.5) a
PreCE	126.1 (65.5) b	117.2 (35.5) b	118.2 (51.0) a	173.4 (40.9) a	245.0 (97.2) b	156.0 (35.1) b	1300.0 (175.5) a
PreSI	184.8 (67.5) b	268.5 (153.2) b	167.0 (69.7) a	211.2 (93.1) a	219.8 (68.1) b	210.3 (65.4) b	1090.7 (218.8) a

*Means followed by different letters in the same column are statistically different ($p \leq 0.01$)

*Means followed by different letters in the same column are statistically different ($p \leq 0.01$).

The optimum design parameters (Figure 1) achieved 100% of the desired fracture load (above 1000 N) and 40% of the desired adaptation (below 200 mm). The best combination of factors to achieve an optimum value of both adaptation and fracture load for the all-ceramic crowns was chamfer finish line, extra-oral scanning and the press technique.

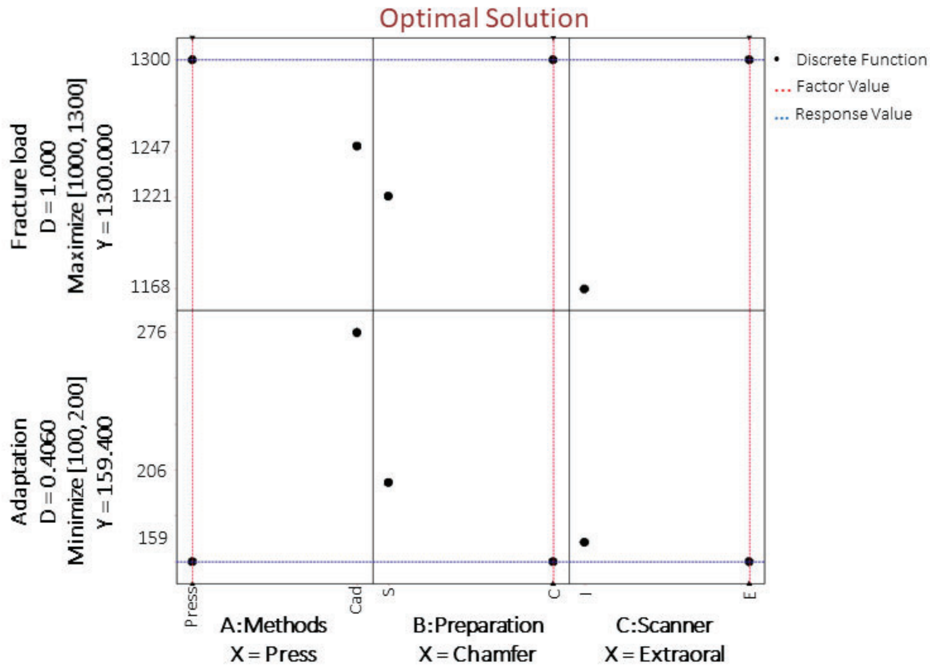

Figure 1. Graph showing the optimal design parameters of the study, combining the chamfer finish line, extra-oral scanning and heat-press method. The fracture load and mean gap thickness chosen as target were 1300 N (minimum 1000 N) and 100 µm (maximum 200 µm), respectively.

All crowns had catastrophic failure after the compressive load test, and fractographic analysis indicated different fracture origins (Table 4). Figure 2 shows a representative image of the fracture surface of crown with a compression curl in the cervical area and twist hackles pointing to the occlusal subsurface, where the critical flaw was located. In Figure 3, the critical flaw showed a radial crack located in the intaglio (cementation) surface of the crown, which was indicated by the presence of a compression curl in the cervical area, twist hackles and hackle lines in the occlusal surface.

Table 4. Fracture origins for each experimental group.

Group	**Fracture Origin**		
	Radial	**Occlusal Surface**	**Not Identified**
CadCI	-	5 (50%)	5 (50%)
CadSE	1 (10%)	6 (60%)	3 (30%)
PreCE	4 (40%)	4 (40%)	2 (20%)
PreSI	2 (20%)	2 (20%)	6 (60%)

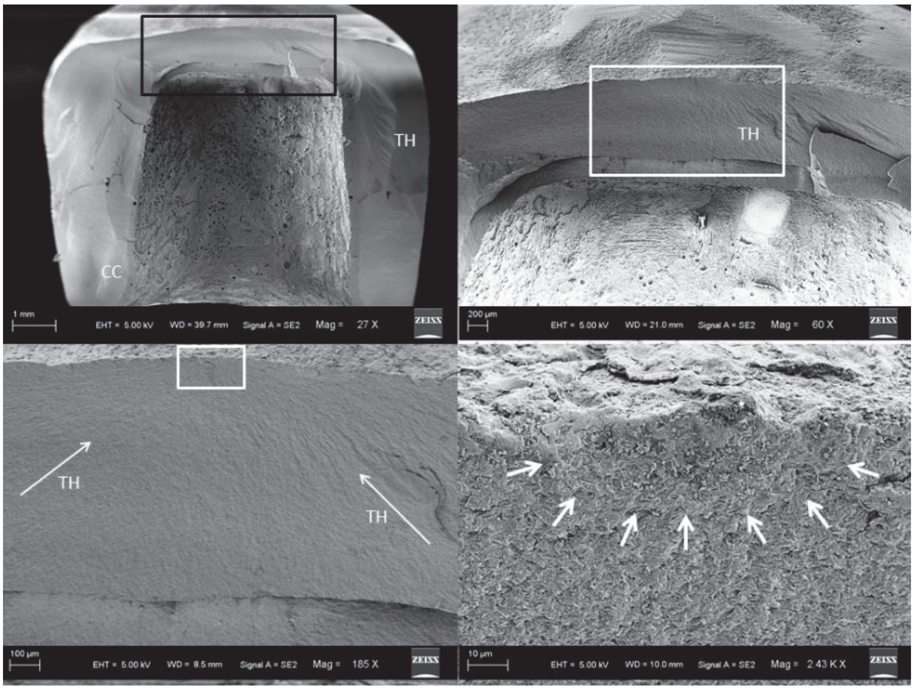

Figure 2. A- SEM image of the fracture surface of a crown from PreCE group tested in fracture load. It is possible to observe fractographic marks, such as compression curl (CC) and hackle lines (HL) indicating the flaw origin at occlusal subsurface (black box), which is magnified in image B and C (White box). D- white arrows showing the critical flaw.

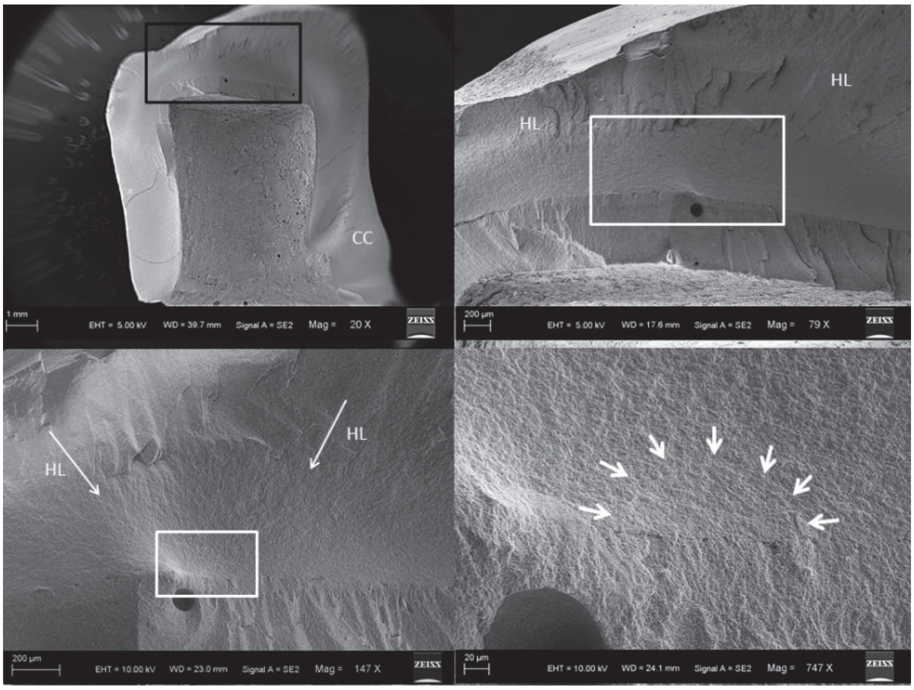

Figure 3. A- SEM image of a crown from PreCE group that failed from a radial crack located in the ceramic intaglio surface. It is possible to observe fractographic marks, such as compression curl (CC) and hackle lines (HL) indicating the flaw origin started at the interface between resin cement and ceramic, in the occlusal area (black box), which is magnified in image B (white box) and C. D- White arrows point to the critical flaw.

4. DISCUSSION

This study investigated how different design-related factors can affect the adaptation and mechanical behavior of lithium disilicate glass-ceramics monolithic crowns, using statistical techniques (DOE) that can optimize the research by reducing costs and time without losing precision and accuracy. A traditional factorial design would require eight groups and eighty specimens. The study hypothesis was partially rejected as the fracture load of LD monolithic crowns was not influenced by the investigated factors; but adaptation was affected by the ceramic processing method.

CAD/CAM processing produced crowns with larger gap thickness in the margin, axial angle and occlusal regions than the press technique, and they had smaller axial gap than pressed crowns. The quality of adaptation for ceramic crowns produced using CAD/CAM is dependent on several factors involved in the processing steps [1, 5, 16, 20]. Nevertheless, in the present study, the scanning method had no effect on the gap thickness; and the same CAD system was used to design the restorations for Cad and Pres groups. Therefore, differences in the crown's adaptation could be attributed to variables related to the CAM subtractive step, including the precision of the milling unit and the burs´ shape, size and granulation. Previous investigations also found larger gap thickness for ceramic crowns produced with CAD/CAM in comparison to other techniques [6, 22]. The combination of 3D printing and press resulted in crowns with smaller gap thickness and a more uniform cement space, corroborating with the literature [30, 39]. A faster and more controlled process can be achieved by replacing the conventional restoration waxing with 3D printing. In addition, the 3D printers used in Dentistry can show a resolution of 16 µm, resulting in similar or better accuracy than milling machines [30, 39, 40].

Similar adaptation between crowns produced with different scanners and abutment finish lines may be related to the quality of the scanning process and equipment. First, the dimensions of the abutment preparations were standardized and the differences between the two types of finish lines investigated may not be great enough to affect the quality of image acquisition by the scanner devices. Second, intraoral scanning was performed in perfect conditions, outside the patient´s mouth, without the presence of soft tissues and humidity. Finally, both pieces of equipment are optical scanners with different strategies of capturing data; but with good accuracy and precision [15, 16, 41]. The extraoral scanner evaluated has a faster scanning speed than the previous ones with lasers, projecting the entire area of the plaster model to the CAM, and they use blue light that is known to cause less interactions with the ambient light during scanning than white light [15]. The intraoral scanner uses a video camera technology for continuous data acquisition that generates a 3D model, and they do not require powder application [41].

Larger occlusal gaps increase the magnitude of tensile stresses under loading at the cementation surface of the crown [7, 13]; while smaller axial gaps are associated with hoop stress [3]. Nevertheless, similar fracture load and failure behavior was observed between crowns produced using CAD/CAM and the press technique. The stress distribution in a multi-layered structure is affected by the mechanical and physical properties of each material as well [42]. Stiffer resin cements, such as the one used in the present study (E=7 GPa), could reduce the deflexion of the ceramic crown during compressive loading and help suppressing the tensile stresses generated in the intaglio surface [41, 43]. In addition, DL has good mechanical properties, being less sensitive to variations in the cement gap thickness.

Failure analysis of the crowns indicated that fractures originated either from the occlusal area or from the intaglio surface of the ceramic crowns. When crowns are subjected to compressive loads, there is a high concentration of compressive and tensile stresses in the contact area with the antagonist, which could lead to chipping, fractures or catastrophic failure; failures mainly originated from the occlusal surface or sub-surface [42]. Tensile stresses are also concentrated in the cementation surface of the ceramic, resulting in catastrophic failures originated from radial cracks [38, 42]. Both failure modes were previously reported for monolithic ceramic restorations that failed clinically [44].

Data obtained with the adaptation and fracture load analysis were combined to predict the optimal design for monolithic DL crowns. The goal for the fracture load was set as 1000 N, considering that this value is well above the average chewing force [36]. For the mean gap thickness, a goal of 100 mm was chosen based in the recommendations for clinical use [11, 12]. The optimum design parameters were chamfer finish line, extraoral scanning and the press technique. Eventhough there was no significant effect of the finish line and scanning method for the dependent variables, crowns with chamfer finish line and produced using the extra-oral scanner were more likely to achieve the desired goals.

This study reproduced the configuration and all the steps involved in the production of a ceramic restoration, aiming to more closely simulate the clinical conditions. Yet, fracture load tests can overestimate the mechanical behavior of ceramic restorations since the effect of cyclic fatigue strength-degradation mechanisms and the slow crack growth phenomenon are neglected [45]. Nevertheless, the fracture load test combined with the adaptation analysis were chosen as they are efficient methods to collect data and can be used to screen the most important variables for design optimization, as recommended by the DOE statistical technique used in the present investigation. A fatigue test is suggested for the final verification of the restoration optimal design.

5. CONCLUSIONS

The best combination of factors to achieve an optimum value of both adaptation and fracture load for the monolithic lithium disilicate glass-ceramic crowns was chamfer finish line, extraoral scanning and the press technique (combined with 3D-printing).

CAD/CAM resulted in larger gap thickness in the occlusal, axial angle and marginal areas and smaller gap thickness in the axial area; whereas there was no effect of the processing method on the fracture load of the ceramic crowns.

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ARTIGO A SER SUBMETIDO À *JOURNAL OF DENTAL RESEARCH*

ARTIGO II

CAD/CAM versus 3D-printing/pressed lithium disilicate monolithic crowns: adaptation and fatigue behavior

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Abstract

The purpose of this study is to evaluate the adaptation and fatigue behavior of lithium disilicate glass-ceramic (LD) monolithic crowns produced by CAD/CAM and Press (combined with 3D-printting) techniques. Thirty abutment preparations with a chamfer finish line were produced with a dentin analogue material and scanned with extraoral scanner. Captured images were processed using CAD software to design a premolar. Blocks of LD were milled using CAD/CAM system. For the Press technique, crowns were first 3D-printed using a polymeric material and the heat-pressing protocol was performed. Crowns were adhesively cemented to the abutments and scanned using micro-CT. Files were processed using NRecon, Data Viewer and CTAn software. Cross-sectional images were analysed using ImageJ in five measuring points: marginal, axial angle, axial, occlusal angle and occlusal. Fatigue test was performed in a MTS universal testing machine (2 Hz, 37ºC distilled water) using an anatomic composite piston, following the step-stress method. Failures were detected with an acoustic system and confirmed by transillumination. A cumulative damage-Weibull distribution (95% CL) was used to analyze the fatigue data. Gap thickness data were analyzed using two-way ANOVA and post hoc Tukey test ($\alpha = 0.05$). The factor processing method was not significant for the adaptation ($p=0,927$); while the factor measurement region ($p<0.001$) and the interaction between factors were significant ($p<0.001$). CAD/CAM resulted in larger gap thickness in the occlusal and smaller gap thickness in the axial angle and axial area. The probability of failure was similar for crowns produced with CAD/CAM and Press. The most frequent failure mode was radial crack. LD crowns produced using the combination of 3D printing and Press technique presented a more homogeneous gap thickness than crowns produced with CAD/CAM. Yet, the fatigue behavior was similar for both strategies used to produce all-ceramic LD monolithic crowns.

Keywords: 3D Printing. CAD/CAM. Ceramics. Dental Prosthesis. Resin Cement.

1. INTRODUCTION

Ceramic restorations are widely used in Dentistry as they meet the aesthetic and functional demands of both anterior and posterior regions of the mouth (Gracis et al. 2015; Kelly and Benetti 2011; Pieger et al. 2014; Reich and Schierz 2013). Currently, lithium disilicate glass-ceramics (LD) have been recognized as an excellent option for dental rehabilitation, being indicated to produce monolithic crowns (Kassardjian et al. 2016; Schestatsky et al. 2019; Zarone et al. 2016). A study stated that LD crowns have a 10% probability of failure in a 20 years follow-up

(Belli et al. 2016), while a systematic review demonstrated a success rate of 96.6% in 5 years (Sailer et al. 2015). Furthermore, a retrospective evaluation after up to 11 years of clinical service, reported a cumulative survival rate of 98.2% for LD single crowns (Teichmann et al. 2017).

There are two distinct methods available to produce LD restorations. One technique is based on high vacuum injection, where ceramic ingots are heat-pressed (Press) into a waxed crown inclusion in a special cast investment. However, a faster and more controlled process can be achieved by replacing the conventional restoration waxing with 3D printing (Alharbi et al. 2018; Jeong et al. 2018; Lee et al. 2017). Data acquisition and processing follow the same steps of the conventional CAD/CAM system, but the subtractive technique is replaced by the additive one (Dawood et al. 2015), and the 3D-printed polymer restoration is processed using the press technique to produce the final restoration (Ottoni et al. 2019). The other technique involves milling pre-crystallized LD blocks using the CAD/CAM (Computer Aided Design/Computer Aided Manufacturing) system (Schestatsky et al. 2019; Zarone et al. 2016). Differences in ceramic processing may result in distinct microstructures, which could affect the mechanical behavior of the materials and, consequently, influence the clinical performance of the ceramic prosthesis (Alkadi and Ruse 2016; Belli et al. 2016; Sailer et al. 2015; Teichmann et al. 2017; Zarone et al. 2016).

Ceramic processing could affect the prosthesis adaptation as well. Variables involved in the CAM/CAM system, such as software limitations in designing restorations, size discrepancy of the cutting tools and tooth preparation geometry may cause misfit and contribute to larger gap thickness for ceramic crowns (Colpani et al. 2013; Guess et al. 2014; Ottoni et al. 2019). On the other hand, the combination of 3D printing and Press results in crowns with a smaller gap thickness and a more uniform cement space (Ottoni et al. 2019). However, few studies are available for this technique and a large number of materials are available for 3D printing, and there may be a difference in the final result of the restoration. While poor internal adaptation may affect the mechanical behavior of prosthetic restorations (Borba et al. 2011; Kunii et al. 2007; May et al. 2012), large marginal gaps are directly related to the degradation of the luting cement and biological problems (Sarrett 2007).

In our previous investigation, a set of statistical techniques called Design of Experiments (DOE) was used to plan the experimental groups and to identify the best combinations of factors to produce all-ceramic LD monolithic crowns. The abutment finish line and scanning method did not influence the crown’s adaptation and fracture load. CAD/CAM resulted in larger gap thickness in the occlusal, axial angle and marginal areas and smaller gap thickness in the axial area; whereas there was no effect of the processing method on the fracture load. The optimum combination of factors to achieve the smallest mean gap thickness and greater fracture load was chamfer finish line, extraoral scanning and the press technique (combined with 3D-printting) (Ottoni et al. 2019). However, a study limitation is that fracture load tests fail to represent the conditions of the oral environment.

Prosthetic restorations are subjected to an aggressive clinical environment. Cyclic loading combined with a humid environment affect the clinical performance of ceramic restorations. Depending on their composition and microstructure, extrinsic and intrinsic fatigue mechanisms may be involved in the degradation of the mechanical properties of ceramics (Belli et al. 2014; Ottoni et al. 2018). The slow-crack growth (SCG) is also present in humid environments, accelerating the chemical corrosion of a pre-existing flaws until reaching a critical size and resulting in ceramic failure (Kelly et al. 2017). In vitro, fatigue tests can be performed to simulate the oral environment. (Kelly et al. 2017; Wendler et al. 2018). In the step-stress method, each specimen is subjected to time-varying stresses until failure occurs or the test is suspended (Borba et al. 2013; Kelly et al. 2017). This methodology is important to prove the optimized design found in our previous study (Ottoni et al. 2019).

The objective of this in vitro study is to evaluate the gap thickness and fatigue behavior of all-ceramic LD monolithic crowns produced by CAD/CAM and Press (combined with 3D-printting). The study hypothesis are that the type of processing method used to fabricate the crowns have no effect on their fatigue behavior; but influence its adaptation.

2. MATERIALS AND METHODS

2.1 Specimen Preparation

2.2.1 Abutment and Piston Preparation

A digital model of an abutment with chamfer finish line was designed using a software (Romi GL240, Romi Industries S.A., Santa Barbara d'Oeste, SP – Brazil). The abutment has 6 mm in height, 8 mm in diameter and 12º of total occlusal convergence (TOC), a radius of 1.2 mm between the cervical area and axial wall, and transitions between the axial and occlusal walls smooth, round and homogeneous (Corazza et al. 2013; Souza et al. 2012). Then, a dentin analogue material (G10, fiber-reinforced epoxy resin) (Facenda et al. 2019; Kelly et al. 2010) was milled using a mechanic lathe (Romi GL240, Romi Industries S.A., Santa Barbara d'Oeste, SP – Brazil) to produce the abutments.

The pistons used to apply the load during the fatigue test were also produced using G10 (Romi GL240, Romi Industries SA, Santa Bárbara d'Oeste, SP - Brazil). The negative copy of the occlusal face of a premolar was used to design the piston, to ensure simultaneous occlusal contacts at three points- tripoidism: lingual cusp ridge of buccal cusp, mesiobuccal triangular developmental groove and mesial pit.

Thirty abutments and pistons were produced and stored in distilled water at 37º C for 15 days to allow hygroscopic expansion of the material and release the residual stresses.

2.2.2 Ceramic Processing

The abutment was inserted in a master model with adjacent teeth to simulate the clinical condition. Then, simultaneous impression technique of the abutments were obtained using polyvinysiloxane (Scan Putty, Scan Light, Yller Biomaterials S/A, Pelotas, Brazil). Models were produced using a special plaster for CAD/CAM (Vita In-Ceram Special Plaster, Vita Zahnfabrik, Germany) and placed in the extraoral scanner (InEos X5, Sirona Dental Systems GmbH, Salzburg, Germany) to capture the images. The CEREC Connect v4.3 software (Dentsply Sirona Deutschland Gmbh, Germany) was used to process the images obtained. All crowns followed the same design of an upper second premolar, using a 90 μm digital cement spacer.

For the CAD/CAM group (n= 15), crowns were milled from pre-crystallized LD blocks (e.max CAD, Ivoclar Vivadent NA, Amherst, NY, USA). Then, crowns were crystallized in a specific furnace (Programat P310, Ivoclar Vivadent NA, Amherst, NY, USA).

For the Press group, crowns were 3D-printed using a polymeric material (VarseoWax CAD/Cast, BEGO, Bremen, Germany) in a 3D printer (Varseo, BEGO, Bremen, Germany). The polymer 3D printed crowns were attached to a silicone ring by wax feed channels of 2.5 mm diameter and included in a cast investment (Bellavest SH, BEGO, Bremen, Germany) through a vacuum mixer (Renfert Twister Evolution, Hilzingen, Germany). After the investment curing (30 min), the set was detached and inserted in the ring furnace (Knebel FAMS, Kota, Cotia, SP, Brazil) at 900 °C for 1 h to volatilize the polymer. Then, the DL ingots (e.max PRESS, Ivoclar Vivadent NA, Amherst, NY, USA) were pressed in a special furnace (Programat EP5000, Ivoclar Vivadent NA, Amherst, NY, USA) at a pre-programmed cycle of 18 min using a maximum temperature of 910°C. As recommended by the manufacture, the crowns were removed from the investment interior, polished with silicone burs to remove any excess of material and cleaned in an ultrasonic bath for 5 min with distilled water.

2.2.3 Cementation

The cementation surfaces of the crowns and the abutments were etched with 10% hydrofluoric acid (CONDAC Porcelana, FGM, Joinvile, SC, Brazil) for 20 and 60 seconds, respectively. The acid was removed using a water/air spray for 30 seconds. The crowns and abutments were cleaned in an ultrasonic bath with distilled water for 5 min and air-dried for 30 seconds. Then, a silane agent (Monobond N, Ivoclar Vivadent NA, Amherst, NY, USA) was applied to all treated surfaces using a microbrush, awaiting solvent evaporation for 1 minute.

A self-adhesive resin cement (Multilink N, Ivoclar Vivadent NA, Amherst, NY, USA) was inserted in the inner part of the crowns and it was seated with manual pressure over the respective abutment. Then, a constant load of 7.5 N was applied in the occlusal surface of the crown for 5 min. A microbrush was used to remove the excess cement. A glycerin gel was applied in the adhesive interface isolating it from contact with oxygen in order to increase the degree of polymerization. Each cement surface was light activated (RADIICAL SDI, Victoria, Australia; 1200 mW/cm^2) for 20 seconds (total time: 100 seconds).

The cemented crowns were stored in distilled water at 37 ° C for 24 hours.

2.3 Adaptation Evaluation using Micro-CT scanning

Each cemented crown was scanned by the SkyScan 1172 micro-CT system equipped with a 10 megapixel camera (Skyscan, Aartselaar, Belgium). The scanning parameters were: accelerating voltage of 70 kV, current of 141 μA, exposure time of 3540 ms per frame, Al + Cu filter, frame averaging of 4, and rotation step at 0.7° (360° rotation).

The x-ray beam was irradiated perpendicular to the preparation long axis, and the image pixel size was 16.98 µm. The x-ray projections were reconstructed using SkyScan's volumetric reconstruction software (Nrecon). Reconstructed slices were saved as a stack of BMP-type files. Beam hardening correction of 20% and ring artifact correction of 10 were used for the reconstruction. Data Viewer (Skyscan, Aartselaar, Belgium) was used to select the volume of interest (VOI), eliminating the scanned empty parts.

The CTVox software (Skyscan, Aartselaar, Belgium) was used to obtain transversal images through the center of the matrix (x-axis), in the mesiodistal direction. As a result, the cross-section was standardized for all crowns, and the same slice - corresponding to the center of the crown - was generated for each crown in BMP-file format. The images were evaluated using an image processing software (ImageJ Launcher, National Institute for Health, Bethesda, USA) and the cement gap thickness was measured in five predefined regions (Figure 1) (Borba et al. 2011; Colpani et al. 2013). One calibrated operator performed all the measurements.

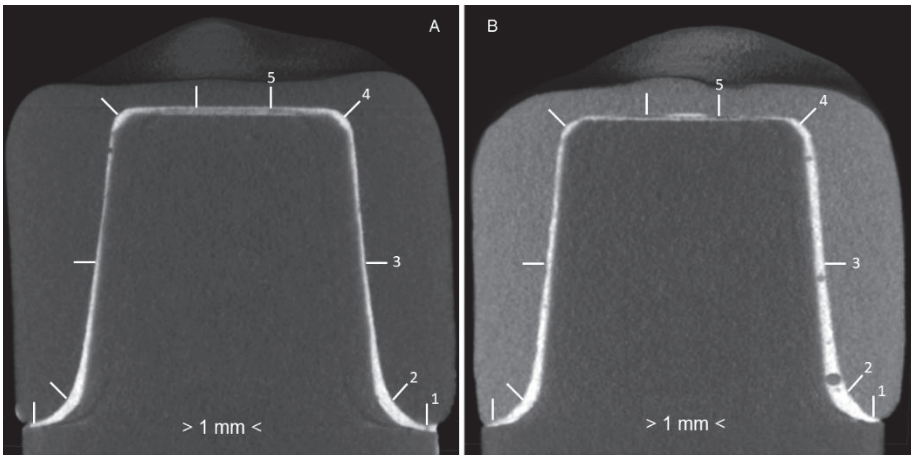

Figure 1. Images obtained using micro-CT and used to measure the gap thickness in five different regions: 1) marginal; 2) axial angle; 3) axial; 4) occlusal angle; 5) occlusal. CAD/CAM (A) and Press (B)groups.

2.4 Fatigue test

Two machines were used to perform the cyclic fatigue tests (MTS FrexTest 60 Controller, MTS Systems Corporation, Eden Prairie, USA), with frequency of 2 Hz. The tests were performed in a water bath container under 37º C distilled water. The load was applied using the anatomic G10 pistons. A new piston was used in each test. Specimens were subjected to four different loading profiles, following the step-stress technique. Mild, medium, aggressive and very aggressive profiles were used:

- Mild = Constant load (200 N per 500,000 cycles) + Step-Stress (step of 13 N every 20,000 cycles);
- Medium = Constant load (250 N per 500,000 cycles) + Step-Stress (step of 13 N every 5,000 cycles);
- Aggressive = Step-Stress (100 N initial load, step of 13 N every 5,000 cycles);
- Very aggressive = Step-Stress (100 N initial load, step of 13 N every 1,000 cycles).

An acoustic system (Song Meter SM2+, Wildlife Acoustics, Concord, USA) was used to detect the initial crack of the crowns. The hydrophone (commonly used to monitor marine animals) was placed inside the water bath, and the sound was recorded in memory cards. No special sound filtering was used. The sound recorded during the fatigue test was analyzed with the Audacity Sound Editor software (Free Software Foundation, Boston, USA) and the number of cycles that corresponded to the first crack (sharp wave peak) was calculated. The same operator checked the audios twice a day. When a large peak was identified, the test was stopped and the crowns were analyzed by transillumination to verify the presence of cracks. If there was no failure, the crown was repositioned and the test restarted from the same point that it stopped, or a new crown was placed if a crack was identified. Failures were classified as: radial crack, cone crack or combined (radial + cone).

2.5 Statistical analysis

Fatigue data was analyzed with a statistical software (ALTA Pro7, Reliasoft) using a cumulative damage-Weibull distribution. The probability of failure (Pf) was estimated for different lifetimes and 50 N load with a 95% confidence interval.

Gap thickness data were analyzed using two-way ANOVA (factor 1: processing method; factor 2: measurement region) followed by a post hoc Tukey test ($\alpha = 0.05$).

3 RESULTS

Table 1 shows the gap thickness (µm) in the different measurement regions for the experimental groups. The factor processing method was not significant ($p=0,927$). The factor measurement region ($p<0.001$) and the interaction between factors were significant ($p<0.001$). CAD/CAM resulted in larger gap thickness in the occlusal and smaller gap thickness in the axial angle and axial area than Press. For the marginal and occlusal angle there were no statistical differences between CAD/CAM and Press.

The intra-groups analysis shows that the CAD/CAM group had smaller gap thickness in the axial area, followed by the marginal, occlusal angle and occlusal area, and resulted in larger gap thickness in the axial angle. The Press group had smaller gap thickness in the marginal, axial and occlusal areas, followed by the cclusal angle, and resulted in larger gap thickness in the axial angle.

Table 1. Results of gap thickness (μm) - mean and standard deviation (SD) of the experimental groups for different measured regions.

Group	Marginal	Axial Angle	Axial	Occlusal Angle	Occlusal
CAD/CAM	120.58 (47.56) Ab	274.15 (53.27) Bd	76.32 (27.44) Ba	199.17 (55.13) Ac	199.21 (41.57) Ac
Press	114.89 (23.18) Aa	313.58 (26.45) Ac	138.07 (15.77) Aa	183.88 (40.32) Ab	121.87 (28.48) Ba

*Different uppercase letters in columns and lowercase letters in rows indicate significant differences ($p<0.05$).

Figure 2 shows the characteristic lifetime (Eta – number of cycles for a probability of failure of 65.3%) for the experimental groups. Fatigue data parameters estimated by the cumulative damage - Weibull distribution and respective 95% confidence intervals (95% CI) were: CAD/CAM group – β= 0.498 (0.293; 0.848); α(0) (cycles)= 39.183 (22.112; 56.254); α(1)= -4.158 (-6.807; -1.508); Eta (cycles)= 8.957 x 10^9 (1.042 x 10^7; 7.695 x 10^{12}); Press group - β= 0.667 (0.402; 1.107.); α(0) (cycles)=30.540 (19.664; 41.415); α(1)= -2.791 (-4.486; -1.096); Eta (Hr)= 3.315 x 10^8 (4.544 x 10^6; 2.418 x 10^{10}); where β is a shape parameter; α(0) is the baseline component of the characteristic strength; α(1) is the load-dependent contribution of the characteristic strength; and Eta is the characteristic lifetime. There's no difference for the parameters between the groups, as the CIs overlapped.

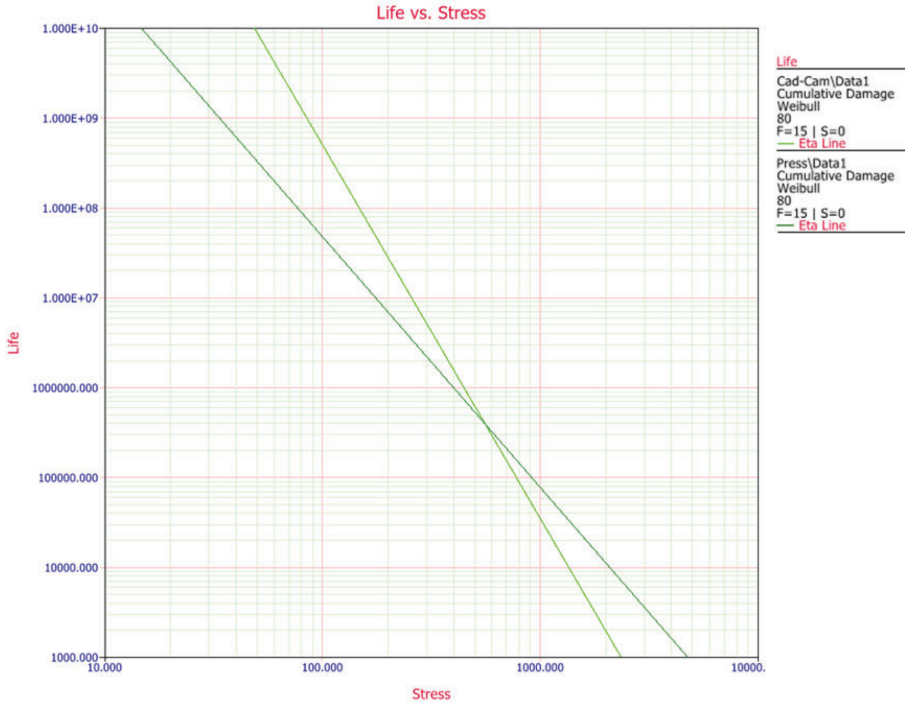

Figure 2. Life (cycles) vs. Stress (N) graph comparing the experimental groups after fatigue test.

The probability of fatigue failure (P_f) at 50 N (value chosen for the intraoral load in the premolar region) for lifetimes representing 1 to 7 years of clinical use (Sakaguchi et al. 1986) were estimated (Figure 3). An increase in the P_f was observed when the number of cycles increased from 240,000 to 1,680,000 cycles. The P_f was similar among groups for the different conditions, as the CIs overlapped.

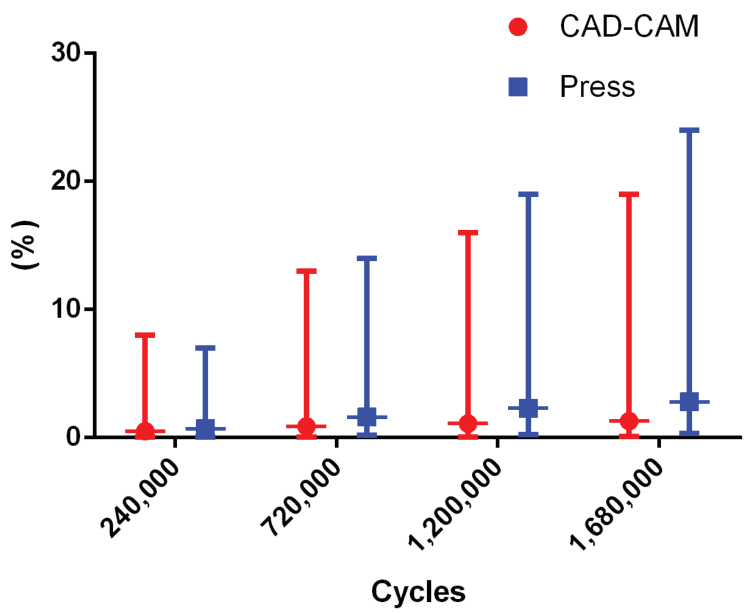

Figure 3. Probability of failure (%) and 95% confidence interval (CI 95%) for different lifetimes and a load of 50 N.

The radial crack was the most frequent failure mode for both groups (Figure 4). Only 2 specimens showed cone cracks in the CAD/CAM group, and only 1 specimen, from the Press group, had a catastrophic failure.

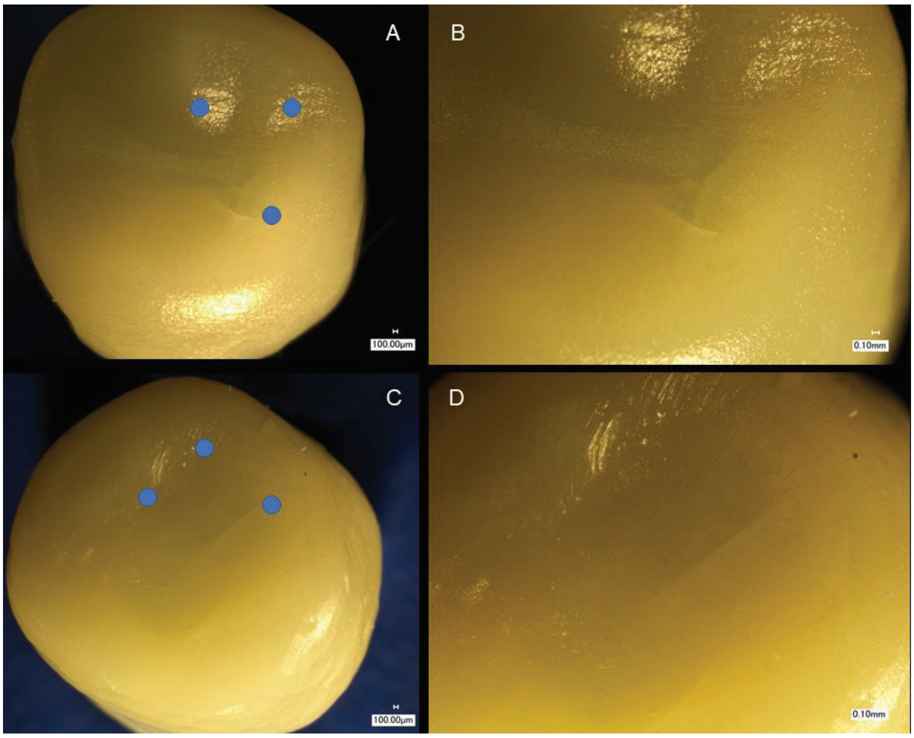

Figure 4. A specimen from the CAD/CAM (A and B) and Press (C and D) groups showing a radial crack that initiated in the intaglio surface, below the region where the load was applied by the piston (blue circles).

4 DISCUSSION

The lithium disilicate glass-ceramic is widely used in the dental clinic to produce all-ceramic restorations. However, the possibility of producing these restorations using different processing techniques can create doubts among clinicians. The present study investigated important clinical aspects (adaptation and lifetime), which help choosing the best treatment for the patient. The addition of 3D-printing in the prosthetic restoration manufacturing process contributes for the current digital dentistry and is validated as an alternative against contraction and deformation of plaster materials, and the inexperience of the laboratory technician (Dawood et al. 2015). Even more, from a methodological point of view, the use of DOE can bring many benefits to all researchers, with a relevant optimization (reduction of costs and time) of the study (Ottoni et al. 2019).

The gap thickness was dependent on the measurement region and processing method, partially rejecting the study hypothesis. LD crowns produced using the Press technique combined with 3D printing presented a more homogeneous gap thickness than crowns produced with CAD/CAM (Guess et al. 2014; Mously et al. 2014). Usually the burs size of the milling machines are 0.6 mm (Jeong et al. 2018; Lee et al. 2017). This limitation can decrease the accuracy of the CAM equipment, leading to a compensation in some areas of the preparation, in an attempt to reach the digital cement space requested during the project in the CAD system, and to a limited reproduction of the uneven surface of the occlusal surface (Lee et al. 2017), corroborating with the previous study (Ottoni et al. 2019).

Nevertheless, the quality of adaptation did not affect the fatigue behavior of DL crowns produced with the different technique as they showed similar failure probability for different lifetimes, accepting the study hypothesis. In the present study, a stiffer resin cement was used (E=7 GPa) and could contribute for a better stress distribution through the multilayer structure (Lawson et al. 2019). This result agree with the previous study that found similar fracture load for CAD/CAM and Press with different gap thicknesses, using the same resin cement (Ottoni et al. 2019). Furthermore, adaptation values are in the recommended range for resin cements (Boening et al. 2000; Pelekanos et al. 2009). However, other studies found greater mechanical degradation for machinable LD after fatigue test in bar specimens (Belli et al. 2014) and better fatigue performance for pressed LD for monolithic crowns with a simplified design and higher chewing frequency (~20 Hz) (Schestatsky et al. 2019). These methodological differences may contribute to a different outcome.

In the present study, an anatomic piston produced with a dentin analog material was used. Fatigue testing was performed in a humid environment and load was applied at the chewing frequency (~2 Hz). Although different load profiles were used, following the step-stress technique, load levels in the range of the biting force were chosen (Borba et al. 2013; Kelly et al. 2017). Thus, the failure modes observed were clinically relevant, showing mostly radial cracks located in the ceramic intaglio surface, below the loading region. Fatigue failure of the crown was registered when the initial crack was detected by the use of an acoustic system. When a crack initiates in fatigue, it will eventually propagate and lead to chipping or catastrophic failures (Kelly et al. 2017; Kelly et al. 2010).

In addition, a complete standardization was adopted in terms of crown geometry, image acquisition, cementation, micro-CT scanning and mechanical testing. The study was carefully designed to minimize methodological effects on the final results and so, extrapolation of the study findings to the clinical scenario can be done. It is expected that LD monolithic crowns produced by CAD/CAM or Press will be able to support the masticatory loads, as long as the processing is carefully done, with rounded prosthetic preparations, visible to the scanners and reproducible by the additive/subtractive machines.

5 CONCLUSIONS

DL crowns produced using the combination 3D printing and the Press technique presented a more homogeneous gap thickness than crowns produced with CAD-CAM. CAD/CAM resulted in larger gap thickness in the occlusal and smaller gap thickness in the axial angle and axial area than Press. However, the fatigue behavior was similar for both strategies used to produce LD monolithic crowns.

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CONSIDERAÇÕES FINAIS

O presente estudo estudou fatores importantes na confecção de coroas protéticas monolíticas. Tais aspectos podem trazer muitos problemas clínicos e entender o funcionamento, melhor forma de execução e consequências dos mesmos no desempenho e longevidades das restaurações é de suma importância clínica. A vitro-cerâmica, métodos de escaneamentos, tipos de preparo, testes executados podem ser o ponto chave na escolha da melhor forma de tratamento.

Além disso, a utilização do Delineamento de experimentos (DOE) para o planejamento e análise dos dados valida-o como uma ferramenta de grande potencial metodológico, pois os resultados do presente estudos foram de igual poder a estudos prévios utilizando metodologias experimentais tradicionais.

Para se chegar até aqui, muitos desafios foram superados. O primeiro passo foi entender como o DOE funcionava e o que deveria ser feito para isso. Chegar a uma padronização no desenho das coroas foi uma tarefa árdua que requereu horas em frente ao CAD/CAM. A utilização da impressão 3D associada a técnica de injeção foi por muito tempo uma dúvida, pois existiam muito poucas referências do uso dessa combinação para fabricação de coroas de cerâmica pura.

Assim, esse estudo recomenda que os preparos protéticos para coroas de cerâmica tenham bordas/ângulos arredondados e bem definidos, permitindo maior precisão do escaneamento e reprodução de detalhes. Com a redução de erros nessas etapas e consequentemente melhor adaptação marginal e interna, o desempenho clínico de coroas monolíticas de dissilicato de lítio será semelhante, independente de ser usinada ou injetada, visto que ambas apresentam comportamento mecânico semelhante.

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